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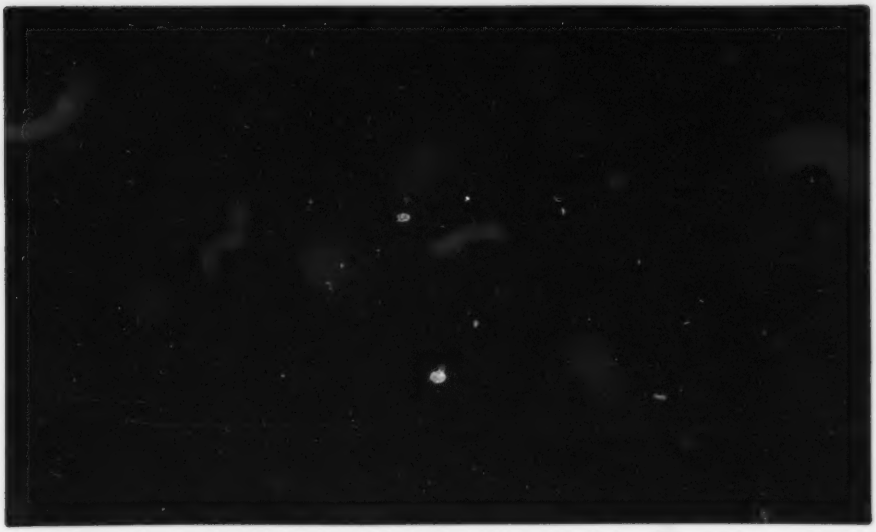
MINERAL DEVELOPMENT AGREEMENT



Canada

Saskatchewan

PREDICTIVE HYPSOMETRY

INCORPORATING LAG

(PHIL)

FINAL REPORT

By

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PHIL Computer Program

As part of its obligations under this contract, Central Canada Potash and its Noranda affiliate, Noranda Technology Centre (NTC), will provide support by telephone and system updates for a four-month period following the submission of this final report. The person to contact is Mr. Andrew Dasys - Tel: (514) 630-9394.

NTC will replace any defective disks delivered with the PHIL programs.

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EXECUTIVE SUMMARY

Central Canada Potash Division of Noranda Minerals Inc., subcontracted to Noranda Technology Centre to provide a subsidence prediction computer program suitable for the prediction of subsidence over the Saskatchewan potash horizon. The project was jointly funded by Saskatchewan Potash Producers Association and CANMET, a part of Energy Mines and Resources Canada.

The resultant model (Predictive Hypsometry Incorporating Lag, PHIL) consists of a front-end (main menu) which allows the user to easily manipulate data handling and access the six other modules of the model. The other modules are the user-interface, preprocessor, subsidence, postprocessor, configure system, print, and plot modules. The model uses state of the art graphic libraries and an in-house developed user-interface and postprocessor. Also supplied with the model is a users' manual.

Calibration of the prediction algorithm to Central Canada Potash's (CCP) block II and International Mineral and Chemical Corporation's (IMCC) K2 mine showed good agreement between predicted subsidence values and actual field measurements.

SOMMAIRE EXECUTIVE

Le Centre de Technologie Noranda dans le cadre d'un sous-contrat de la division Central Canada Potash de Noranda Minérales Inc. a été mandaté pour développer un logiciel afin de prédire la subsidence au dessus des couches de potasse de la Saskatchewan. Le projet était subventionné par l'Association des Producteurs de Potasse de la Saskatchewan et CANMET qui est une division d'Energie Mines et Resources du Canada.

Le logiciel proposé (Predictive Hypsometry Incorporating Lag, PHIL) comprend un menu principale qui facilite la manipulation des données et permet un accés efficace aux six autres modules inclus dans le logiciel. Les autres modules sont; l'interface à l'usage, le processeur, le module de subsidence, le postprocesseur et les modules d'imprimerie et de dessin. Le logiciel utilise des libraries de fonctions graphiques commerciales ainsi qu'un interface à l'usage et un postprocesseur dévelopé au Centre de Technologie Noranda. Un manuel de l'utilisateur est également inclus.

Lors de la calibration de l'algorithme au block II de la Central Canada Potash (CCP) et de la mine K2 de l'International Mineral and Chemical Corporation (IMCC), les predictions de subsidence ont démontré une bonne corrélation avec les mesures de terrain.

SUMMARY

Central Canada Potash Division of Noranda Minerals Inc. (Project Leader) subcontracted to Noranda Technology Centre to provide a subsidence prediction computer program suitable for the prediction of subsidence over the Saskatchewan potash horizon. The project was jointly funded by contributing companies of the Saskatchewan Potash Producers Association (SPPA) and CANMET, a part of the Energy Mines and Resources.

The resultant model (Predictive Hypsometry Incorporating Lag, PHIL) consists of a front-end main menu which allows the user to easily handle data and access the seven other modules of the model. The other modules are the user-interface, preprocessor, subsidence, postprocessor, configure system, print, and plot modules. The model uses state of the art graphic libraries and in-house developed user-interface and postprocessor. Also supplied with the model is a user manual. PHIL is designed to run of IBM XT or XT compatibles with a hard disk, 640 K memory and MS-DOS 3.0 or higher.

The main menu of PHIL is written in the "C" language and contains routines which allow the user to:

- configure the system;
- enter the user-interface to edit input parameters;
- execute the preprocessing and subsidence modules which import the required data files;
- configure and view the postprocessor graphics;
- print data files;
- plot graphics.

The user-interface is essentially a user-interactive editing package using pop-up window routines developed in Turbo Pascal. Within this module, the parameters and definitions required for the simulation are defined. The user-interface creates two command files required by the preprocessing and subsidence modules.

The preprocessor and subsidence module are developed in Fortran with the preprocessor primarily used to define mine and surface geometries, the topology of the surface, and the mining sequence. The subsidence module contains the prediction algorithm for the simulation. Also contained is an optimizing routine which numerically optimizes the six principal parameters of the prediction algorithm.

The postprocessor is developed in the "C" language using GraphiC™, a graphics library. Four types of plots are available:

- XY graphs
- Extraction plots
- Contours
- Composite plots

The subsidence prediction model has been calibrated to block II of CCP and the K2 mine of IMCC. The results obtained agreed with actual measurements with 8.7% and 4.7% RMS error respectively.

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1. INTRODUCTION

Presently, Saskatchewan potash producers mine potash at extraction ratios in the range of 25% to 40%. Mining at these extraction ratios typically results in approximately a half meter of surface subsidence. Yearly surveys are performed to verify this. The industry recognizes that increasing the present extraction ratios to a level of 50% to 60% would have enormous economic implications. Reserves would be doubled, capital outlay minimized, and unit production costs decreased.

Subsidence, being a function of extraction, (1,2), would increase if extraction ratios were to be increased. It would therefore be essential to be able to predict the magnitude of subsidence which would be associated with new mining methods characterized by increased extraction ratios. This would ensure that the effect of mining on overlying infrastructure could be properly evaluated and in the case where the resulting subsidence were critical, proper precautions taken.

In the second half of 1986, the Saskatchewan Potash Producers Association reviewed different projects for the fiscal year (April 1986 - March 1987). Research projects were to be funded under the Mineral Development Agreement between the Province of Saskatchewan, the Federal Government and industry. Under the terms of the agreement, the costs for mining research contracts were to be split 50% to industry and 50% to the federal government through the Department of Energy and Mines, CANMET.

Subsidence can be predicted using both analytical/mechanistic and empirical techniques. The analytical/mechanistic methods include closed form elastic formulation, generalized influence face elements, and two numerical techniques - the void volume and finite element methods. More recently, boundary element modelling has been used for geomechanical predictions however, it has not yet been tested for subsidence prediction. Of these prediction techniques, finite element analysis has seen the most wide spread use. However, in modelling subsidence over potash mines which are characterized by approximately 1000 m of overlying strata, accurate predictions would require too much resident memory for the microcomputers normally found at potash operations. Large elements could be used to overcome memory limitations at the expense of accuracy.

Empirical techniques which can be used to predict subsidence over potash mines include graphical methods and profile, influence, and complementary influence functions; and incremental design methods. These methods have been predominantly formulated for U.K. coal fields and are therefore characterized by parameters that are specific to given geological settings and do not properly account for the time dependent creep associated with the Saskatchewan potash horizon.

The Department of Mineral Engineering, Pennsylvania State University, developed a computer program (SPASID) to predict surface subsidence over coal mines under contract to the United States Bureau of Mines (USBM). With SPASID, subsidence resulting from mining can be calculated by either of two influence functions; Knothe's or an elastic function. Both of these functions are related to the volume of material extracted at a given time. Included with the program is a system identification module which can be used to optimize site specific parameters using the method of steepest descent with golden section search.

Work in 1984 at Noranda Technology showed that although SPASID could be used to predict subsidence over potash mines in a given year, predictions for others years based on this calibration did not correlate well with the actual data (2). It was concluded that the time dependent nature of creep in potash mines was not properly accounted for by the characteristic time function of the SPASID program. Other shortcomings of the program were also noted during the investigation. In particular, that the user- friendliness and interactiveness could be improved by using newer techniques and that some bugs still existed in the downloaded version of the program. However, it was recognized that SPASID's structure was very good and would be of considerable benefit in producing a program for subsidence prediction over potash mines.

A previous Mineral Development Agreement project, headed by Dr. P. Mottahed of the Potash Corporation of Saskatchewan with contributions from Dr. Will Bawden of the Noranda Technology Centre, had investigated subsidence in Saskatchewan potash mines. The results were presented in a CANMET report, "Assessment of Possible Problems in Regional Mine Stability with Future Mining of Saskatchewan Potash" in March 1985. The work focussed on the zone area method for the prediction of subsidence over potash mines. The zone area method is a simple influence function based on extraction. The CANMET report concluded that subsidence resulting from mining potash occurred in two phases (2). First, a rapid component of ground movement followed by a constant longer term component. It was further highlighted that a time lag exists between initial mining and surface displacements. This lag was typically a number of years.

Having investigated both SPASID and the zone area method and their applicability to potash mines, it became evident that incorporating the zone area method into SPASID would yield a useful subsidence prediction technique for the Saskatchewan potash industry.

Noranda Technology Centre proposed that they could modify SPASID to meet the constraints of the Saskatchewan potash mines. These constraints, as mentioned above, were based upon the visco-elastic nature of the Prairie Evaporite Formation and resulted in a lag of subsidence as measured on the surface behind the mining of the room below that surface.

Central Canada Potash proposed the project to the Saskatchewan Potash Producers Association. The project was accepted in 1986.

2. PREDICTION TECHNIQUES

Subsidence over potash mines can be predicted either by empirical methods or analytical/mechanistic methods. The analytical methods are based on the stresses induced by the mining geometry and the overburden's response to this while empirical methods have been formulated from observed data. Table 1 outlines available methods.

2.1 Empirical Methods

Being based on observed data, empirical techniques by nature treat overburden as a homogenous entity without regard to mechanistic properties. The formulation of the predictive equations is such that the varying mechanical properties of the different geological strata be treated as one. There are two types of empirical prediction techniques, graphical and mathematical.

2.1.1 Graphical Methods

Graphical prediction techniques have been developed for both longwall, and room and pillar coal mining (3,4). In both cases the nondimensionalized graphs allow the engineer to predict subsidence or a subsidence factor based on depth and mining geometry. A room and pillar example is shown in Figure 1. It is essential in using graphical techniques that the mining and geology of the operation be quite similar to those of the case histories used in formulating the graphs. It should also be noted that limited data was used in the case of room and pillar coal mining. A more detailed description of graphical techniques is included in reference 1.

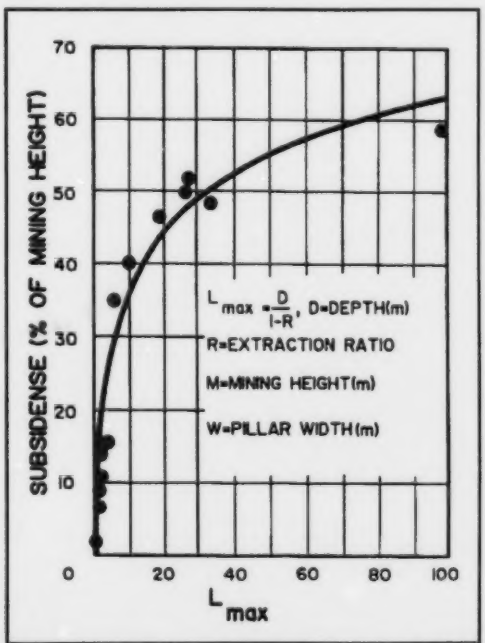

Figure 1 : Subsidence Above Room and Pillar Mining. [After Ref. 3]

2.1.2 Mathematical Methods

Included in the mathematical empirical prediction techniques are profile, influence, and complementary influence factions along with incremental design. The underlying principal in these techniques is that a mathematical function is derived from observed subsidence data and then applied for predictive purposes. Although characterized by some site specificity, the variables found in the functions allow more universal application.

Table I : Subsidence Prediction Techniques

SUBSIDENCE PREDICTION TECHNIQUES	DESCRIPTION
EMPIRICAL	
Graphical	
NBC	- developed from U.K. longwall coal fields -specific to these geological settings - relates expected subsidence to mining depth and geometry in a nondimensional manner.
Room & Pillar	- developed from limited room and pillar subsidence data - relates a subsidence factor to seam thickness, depth, pillars, extraction
Mathematical	
Profile Functions	- require actual field measurements - relates subsidence at a point to max. subsidence as measured to define a half subsidence profile - site specific
Influence Functions	- based on the theory of super-position and observed data where a function has been defined for the extraction of infinitesimal elements - time can be included
Complimentary Influence	- similar to influence functions with the effect of unmined elements Functions included
Incremental	- based on the assumption that Design observed data reflects the mechanical properties of overburden - developed for U.K. coal fields - time is not considered
ANALYTICAL/MECHANISTIC	
CLOSED FORM	- based on elastic theory and the Elastic deformation of a semi-infinite Formulation transversally isotropic plate - two elastic constants are used to define overburden - simple mining geometries assumed
Generalized Influence Face Elements	- similar to influence functions except elastic analysis is used - filed measurements aid analysis
Void Volume	- include roof and pillar failure along with time dependent strain and is a function of mined volume
Finite Element	- rock mass modelled as elements in 2 or 3 dimensions -given stress/strain relationship dis-continuities and complex geometries - best supported by field data

2.1.2.1 Profile Functions

Using profile functions to predict subsidence requires that some field measurements be made. From these measurements half the subsidence trough can be extrapolated. Profile functions are in the form:

$$s = S*f(R,x,c)$$

where, s : subsidence at a point
S : maximum subsidence at the centre
R : critical radius
x : horizontal distance from inflection point
c : either a constant or a function

Figure 2 shows an example of a profile function. In using profile functions, the point of inflection must be determined in the field because it is used along with seam depth to define the subsidence point.

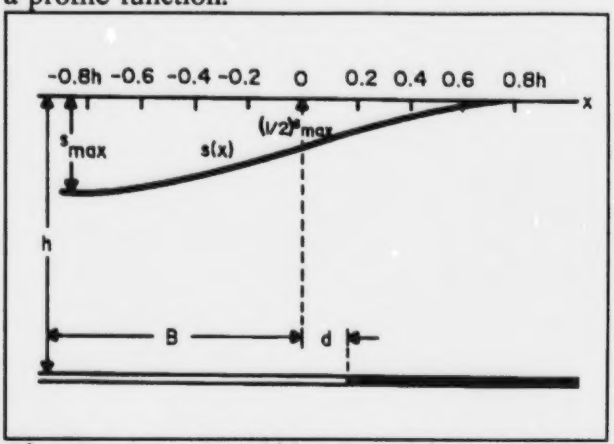

Figure 2 : Profile Function [After Brauener (5)]

2.1.2.2 Influence Functions

There are a variety of influence functions, however, all are characterized by the underlying principle that the subsidence at a given point can be represented by the sum of the influence of all infinitesimal elements extracted below that point, within a critical radius. Therefore, subsidence can be expressed as:

$$S = \int_A p(r)\, dA$$

where, S : subsidence
p(r) : influence function
A : zone of influence.

Generally, the influence function, p(r), is a function of the subsidence at the panel centre, the critical radius or the zone of influence, and the position of the element extracted relative to the subsiding point. It has been shown that sufficiently large pillars result in over prediction of subsidence when calculated by influence functions (5). This can be accounted for when using influence

functions which incorporate an edge effect.

Figure 3 illustrates the theory of superimposition.

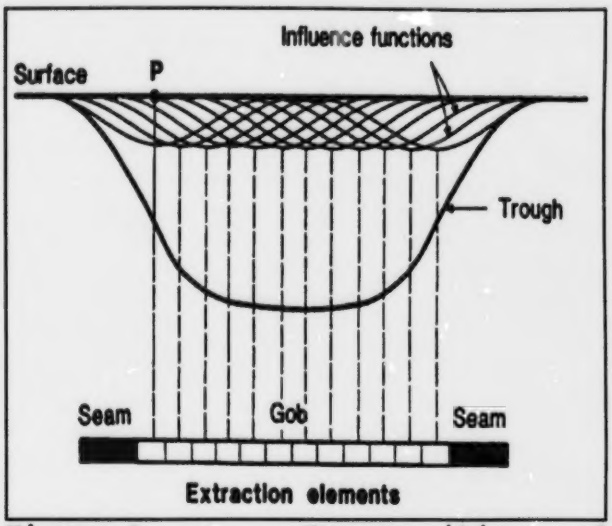

Figure 3 : Superposition of Influence Functions. [After Ref. 5]

2.1.2.3 Complementary Influence Functions

Complementary influence functions, like influence functions, are based on the theory of superimposition. However, the effect of unmined areas also have an influence as shown in Figure 4 where the unmined element acts as a support. The surface is assumed to behave elastically.

2.1.2.4 Incremental Design

Coates formulated the incremental design technique from measurements above U.K. coal fields (7). His assumption was that the ground movement reflected the mechanical properties of the ground and the mechanisms which govern deformation. Initial measurements are used to predict subsidence as mining progresses.

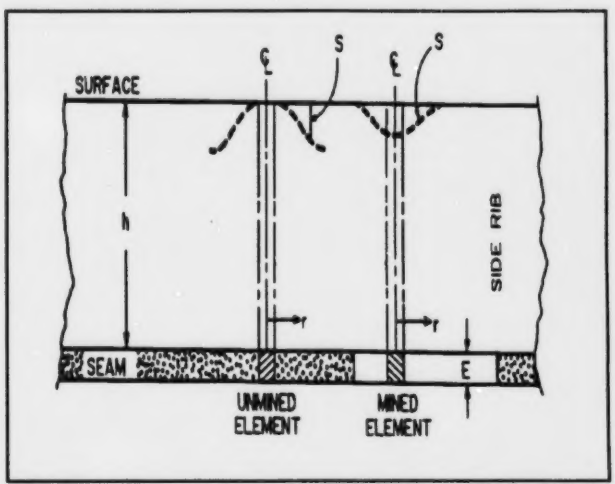

Figure 4 : Complementary Influence Functions [After Ref. 6]

2.2 Analytical/Mechanistic Methods

Analytical/mechanistic methods of predicting subsidence are based on the physical properties of the overburden and its response to mining induced stresses. These include closed form elastic formulation, generalized influence face elements, void volume, and finite element methods. As with empirical methods, a more detailed description can be found in reference 1.

2.2.1 Closed Form Elastic Formulation

Closed form elastic formulation is based on elastic theory where the mining seam is considered a thin slit and the overburden's response to the removal of it (8). The overburden is considered to be a semi-infinite transversely isotropic plate whose planes of symmetry are parallel to surface. Closed form elastic formulation assumes very simple mining geometries and overburden properties. Nonetheless, some success has been achieved for U.K. longwall coal mines.

2.2.2 Generalized Influence Face Elements

Similar to influence functions, influence face element analysis sums the contribution of each element extracted to determine subsidence at a point on surface. However, the relationship to determine the contribution to subsidence of each element is found through elastic analysis rather than empirical relationships.

This method can be used if three conditions are met:

- the mathematics modelling the overburden adequately describes its physical properties,

- closure of the back and floor must be known,

- in the case of complex mining geometries, numerical integration techniques must be used.

The principles of generalized influence face elements can be extended to include frictionless laminated, homogenous isotropic medium, homogenous transversely isotropic, and multi-membrane models.

2.2.3 Void Volume Methods

Munsen and Benzely (9) have proposed a void volume model for subsidence prediction based on three modes of failure. The modes are progressive roof and pillar failure and recompaction. The governing equation:

$$S = aV$$

where,
S : subsidence
a : subsidence parameter
V : volume mined

assumes that the volume mined is filled when the back and pillars fail with an associated bulking factor. This material then is recompacted with time. Therefore, subsidence results from the initial failures followed by a longer term

2.2.4 Finite Element Analysis

Finite element analysis is based on simulating overburden with a number of discrete idealized elements. Each element deforms according to a given stress-strain relationship while compatibility and equilibrium is maintained with all other elements. Both two and three dimensional analyses can be performed. Finite element analysis has the advantage that complicated mine and surface geometries can be evaluated and discontinuities can be included. However, considerable background work investigating the stress-strain relationships and the overburden's material properties would be required before use. Another limitation of finite element analysis is that predictions become more accurate with the number of elements. Therefore, computer simulations can require considerable time and memory.

3. ZONE AREA METHOD

The zone area method proposed by Marr (10) and then later reported be Steed et al (2) is a simplified influence function. Consequently, it has the advantages of being able to incorporate complex mining geometries and time dependence. The zone area method defines a zone of influence for surface monuments for which any extracted element will contribute to the subsidence of that point. The zone of influence is divided into a series of concentric rings which are given a weighting factor. Therefore, subsidence can be expressed as:

$$S = f(a_1xA_1 + a_2xA_2 + \ldots + a_nxA_n)$$

where, a_n : weighting factor
A_n : percent extracted in the zone.

3.1 Applicability of the zone area method to Potash Mining (after Ref. 2)

The work by Steed et al can be summarized as follows:

Subsidence data was collected from five producing potash mines located in southern Saskatchewan. Cooperating operations included Central Canada Potash (CCP), a member of the Noranda Group, and the Allan, Cory, Lanigan and Rocanville divisions of the Potash Corporation Mining Ltd. (PCS-M). Information concerning the current subsidence survey technique and practice, measured results, and geometry of the mine workings was collected. Three of the five mines employ a pillar panel layout. Saskatchewan Potash mining methods are described by Jones and Prugger (11).

Observations of the angle between the horizontal and the line connecting the edge of the workings to the point of zero subsidence lying outside of the workings ranged between 46 and 68 degrees. This is what defines the zone of influence for influence functions and the zone area method. Some of the survey data indicated uplift outside the edge of the workings, which generally resulted in a large observed angle. From the findings the zone of influence contributing to the subsidence of a point was assumed to be a circle of radius equal to the mining depth. This circle was further divided into 7 equally spaced concentric rings, to represent the zones of influence.

A 3962 meter CCP survey line was initially used to investigate applicability of the method. It consisted of 21 stations overlying a chevron panel mining area, achieving a panel extraction of 26.5%. Mining progressed in a retreating mode towards the shaft, from west to east. The survey is aligned in the direction of mining advance.

The CCP data suggests that once mining advances beyond the zone of influence of a surface station, subsidence continues at a remarkably constant rate. Comparison between the constant subsidence rates above the CCP workings and the extraction within the range of influence of the monuments indicates a nearly linear relationship between extraction and subsidence rate (Figure 5). The extraction considered was the "panel" extraction and included both the mining rooms and yielding wing pillars.

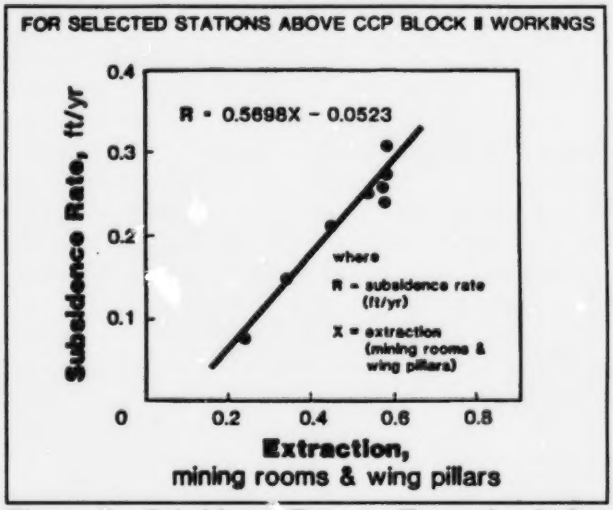

Figure 5 : Subsidence Rate vs. Extraction [After Ref. 2]

The observed steady state of subsidence may result from salt creep in response to mining induced stress increase and removal of restraint. The above leads to the possibility that the observed subsidence occurred in two stages. Upon mining one factor contributing to surface subsidence is initial room convergence. The second factor is flow of the surrounding salt into the rooms. Salt rock is known to have elastic strength in the order of a few MPa (Salamon (12)), while the original superincumbent load at this depth is in the order of 23.5 MPa. The pillars, floor and back of the opening react to the changed stress field by creeping towards the opening.

The prediction of subsidence based on the above observation requires knowledge of three site functions:

a) the weighting (ring weighting in PHIL) of the contribution of extraction within the zones surrounding the point, to subsidence of the point;

b) the function relating the influence of extraction to the long term constant rate of subsidence of a point;

c) the function relating the influence of extraction to the initial contribution towards subsidence of a point. The above must be determined from existing data.

3.2 Case Studies

From the five mines surveyed, three survey lines were chosen to test the applicability of the subsidence prediction method due to the availability of continuous sets of data. The mining height for all three mines was approximately 3.4 meters.

3.2.1 CCP

With the CCP data, the subsidence rate was found to be proportional to the panel extraction ratio within the area of influence. No weight factor was then assigned to the separate zones within the influence area surrounding each point in this case. Function b) was derived from the relationship of extraction to subsidence rate, (Figure 5). Function c) was assumed to be proportional to extraction and provisions were made within the computer program to determine how many years this function would be applicable. This value was adjusted until a visual best fit of the data resulted and took on the following value:

$$S = 1.50X$$

where, S = subsidence attributed to function c)
X = extraction (mining rooms and wing pillars)

The results are shown in Figure 6.

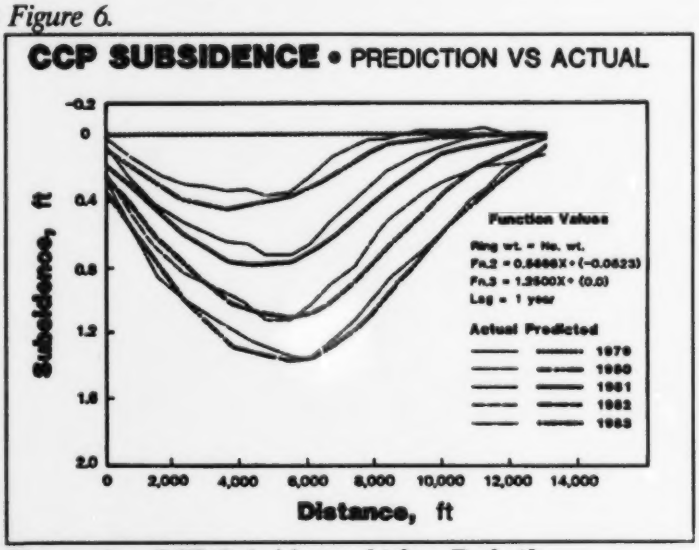

Figure 6 : CCP Subsidence [After Ref. 1]

3.2.2 Lanigan

The Lanigan mine employs a pillar panel method of mining with extraction ranging between 34 and 48% within a panel. Mining beneath the survey line considered began in 1979. Prediction of subsidence using the functions applicable to the CCP case resulted in a very shallow subsidence profile compared to that actually observed. When function c) was based on an influence function derived from observational and probability considerations used with German coal mines (Braeuner (5)), the predicted results more closely represented the observed case (Figure 7). The value of

function b) was represented by R = 0.4 X and function c) by S = 0.2 X with 0.5 year lag employed.

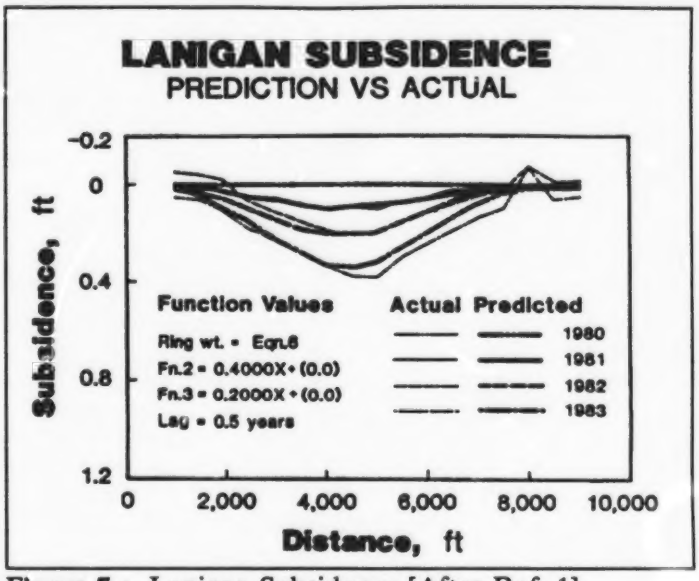

Figure 7 : Lanigan Subsidence [After Ref. 1]

3.2.3 Cory

The Cory mine uses a chevron panel mining method, with an individual panel extraction of approximately 64% and overall extraction in the range of 38-42%. Mining beneath the survey line began in 1976 with subsidence surveys beginning in 1977. Zone weightings used with the CCP case again resulted in a shallow predicted subsidence profile as compared to the actual case. Weighting the zones according to the influence function used with the Lanigan case, and using the same value for function b) as in the CCP case resulted in fairly good correlation with measured data. A value for function c) of S = 1.25 X was used with a lag of 0.0 years.

3.3 Discussion of Results Found with Zone Area Method

From the subsidence data collected over a relatively short time period, it was observed that the total subsidence of ground above Saskatchewan potash mines may be represented by two stages of development. At some time after mining an initial component of subsidence is expressed on surface, followed by long term steady state subsidence until complete closure has occurred. The zone area method of subsidence prediction, employing functions to represent the initial and constant rate of subsidence based on extraction was found to predict subsidence to a reasonable degree of accuracy. The magnitude of initial subsidence and the rate of long term subsidence are site specific and depend on the mining method employed mining seam and overburden geology. Other factors that might influence these functions, which would have to be determined by future research, would include mining height, mine sequencing, discontinuities in the mining zone and overburden and effect of seismic events. In the future, as additional subsidence data becomes available, the accuracy of the present observations may be tested and improved.

A larger initial contribution to subsidence was observed with chevron panel mining rather than with pillar panel mining. A possible explanation is that the chevron mining technique is designed to allow wing rooms to collapse, thereby relieving stress in the areas of advancing entries. This technique should allow a larger volume of rock to move into the openings initially than with pillar panel mining.

4. SPASID
(after Ref. 13)

SPASID (Subsidence Prediction and System Identification) was developed by the Department of Mineral Engineering, The Pennsylvania State University under contract to the United States Bureau of Mines (USBM). The program uses the influence function method. It has two primary functions:

- the precalculation of ground movements due to proposed underground mining,

- the identification of the system parameters from known movements.

It further serves as a means to graphically display results if the correct hardware is available.

The program itself, consists of four separate but dependent modules which are sequentially run in either batch or interactive mode. Figure 8 outlines the interactions of the modules.

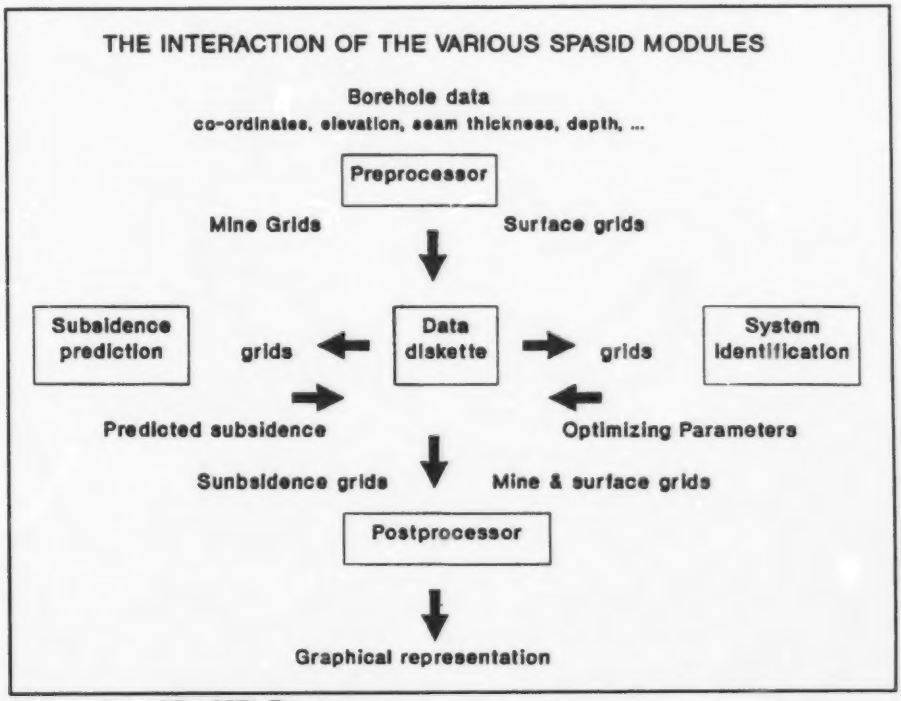

Figure 8 : SPASID Program

4.1 Preprocessor

The sole purpose of the preprocessor is to generate mine and surface grids for the other SPASID modules. Drillhole data is input and from this, surface and mine grids can be generated. The preprocessor can be used to generate two types of mine grids, longwall panels or rooms and pillars; the former being a type 1 grid and the latter, a type 2. The difference between the two is that a type 2 grid allows the user to leave pillars unmined whereas, a type 1 grid necessarily simulates the removal of all material contained within the grid by linear interpolation between successively dated grid lines. This occurs whether or not the grid lines defining a would be pillar have been dated differently. Therefore, using type 1 grids for a potash mine necessitates that each chevron panel be defined as a separate grid and consequently, the maximum number of grids allowed (twelve), is soon surpassed.

4.2 Subsidence Prediction

Once the preprocessor has been used to properly define mine and surface grids along with extraction schedules, the subsidence module can be used to predict subsidence using either an elastic influence function or Knothe's influence function. The assumption that subsidence is directly related to the volume of material extracted pertains to both and can be expressed as:

$$w = t \sum_{i=1}^{n} f_{vi} \frac{(ri)}{(b)} \frac{Ai}{b^2} \qquad U_r = t \sum_{i=1}^{n} f_{Hi} \frac{(ri)}{(b)} \frac{Ai}{b^2}$$

where:

w	: vertical displacement
U_r	: horizontal displacement
t	: seam thickness
f_v, f_H	: influence functions at distance, r
r	: horizontal distance from subsided point
b	: radius of the zone of influence
A	: X-sect area of the extracted volume.

Therefore, SPASID can be used to find both vertical and horizontal displacements. The difference between the two functions lies in the calculation of f_v and f_H. For the elastic influence functions:

$$f_v = \frac{\tan \phi}{2\pi(\alpha_1-\alpha_2)} (R_1^{-3} - R_2^{-3}) \qquad f_H = \frac{\alpha_1 \alpha_2}{2\pi(\alpha_1-\alpha_2)} \frac{r}{b} (R_1^{-3} - R_2^{-3})$$

$$= C_v (R_1^{-3} - R_2^{-3}) \qquad = C_H \frac{r}{b} (R_1^{-3} - R_2^{-3})$$

Where: ϕ = limit angle
α = functions of elastic constants $\alpha_1 < \alpha_2$

and:

$$R_i = \left(\frac{r_i}{b}\right)^2 + \frac{(\tan \phi)^2}{\alpha_i}$$

$$= \left(\frac{r_i}{b}\right)^2 + k_i^2, \; k_1 < k_2$$

Consequently, the elastic influence function can be considered to contain two shape parameters, k_1 and k_2, and vertical or horizontal coefficients depending on which displacement is being calculated.

Knothe's influence functions are more empirical and are represented by:

$$f_v = C_v \exp(-\pi N) \left(\frac{(r)}{(b)}\right)^2 \qquad f_H = C_H \exp(-\pi N) \left(\frac{(r)}{(b)}\right)^2$$

where C_v, C_H, and N, a shape factor, have to be experimentally determined.

Two other important parameters built into the calculation of subsidence are the lag and edge effects. The former specifies the amount of time to reach full subsidence and is exponential and the latter quantifies the reduction in calculated subsidence as the result of the edge of workings.

Other parameters that can be specified by the user are the limit angle pitch factor, and subsidence factor (part of the edge effect). These have only a minor effect on the accuracy of the prediction and can probably be left at their default values. A summary of all the parameters is included in Table 2.

Table II : The Parameters Used in the Influence Functions that are User Specified

INFLUENCE FUNCTION	PARAMETERS INCORPORATED
ELASTIC	- K_1 , K_2 : shape factors - C_V, C_H : vertical & horizontal coefficients - pitch factor (for pitching seams) - edge effect - lag effect
KNOTHE'S	- N: shape factor - C_V, C_H: vertical & horizontal coefficients - pitch factor - edge effect - lag effect

4.3 System Identification

The System Identification module is used, once subsidence has been initially computed, to determine the optimal site and subsidence parameters using numerical methods.

In the case of Knothe's influence function, the secant method is used to find C_v, C_H, and N for different values of the lag and edge effects. The optimal solution is characterized by the smallest R.M.S. error.

The parameters C_v, C_H, K_1 and K_2 must be optimized for different values of the lag and edge effects for the elastic influence function. Therefore, the numerical optimizing method of steepest descent with Golden Section Search is used to adjust these parameters.

4.4 Post Processor

The post processor can be used to plot xy, perspective and contour plots of surface, mine, and subsidence grids. Scaling and sizing is done automatically.

4.5 Discussion of Results found with SPASID for CCP Line #1

To run SPASID for CCP Line #1, block II was divided into 9 rectangular mine grids which were mined according to the schedule supplied by CCP. The dimensions of the grids closely corresponds with the 60% local extraction and 30% overall extraction at CCP in Block II. Only vertical subsidence was analyzed as this was the only data available.

Preliminary trials indicated that the predicted subsidence for room and pillar mining obtained by Knothe's influence and the elastic influence function could be made identical by adjusting site and subsidence parameters accordingly, as shown in Figure 9. Therefore, further investigations included only Knothe's influence function because of its relative simplicity.

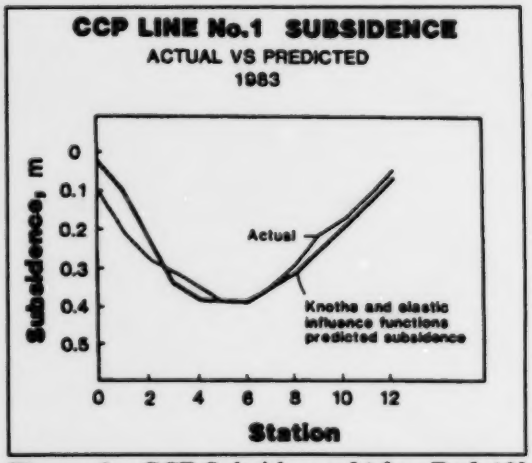

Figure 9: CCP Subsidence [After Ref. 13]

Figure 9 also shows that the predicted subsidence matches actual data better on the east side of line #1. The shape of the eastern half of the curve was more easily

approximated throughout the analysis. This was achieved by treating stations 1 to 7 independently. Interestingly, mining had occurred earlier under these benchmarks.

It was previously noted that subsidence over potash mines occurs in two stages because of two stage convergence:

- rapid convergence of the back to floor immediately after mining (100-200 days),

- convergence due to creep of the pillars because of superincumbent load at depth.

SPASID has only the former phenomenon incorporated into subsidence prediction via its lag effect. In essence, the influence functions can be used in an exponentially decaying fashion, however, this does not account for two stages of convergence. Using this, the user can specify the amount of time required for complete subsidence, due to extraction, to occur. It was found that, even though a good match can be found for any given year, as the date subsidence is calculated for deviates from the year of initial curve fitting, the fit of predicted subsidence to actual subsidence gets worse. This is illustrated in Figures 10 and 11 where this date was changed from 1982 through 1979, (indicated by successively shallower curves); the match becomes worse and in fact, the overall shapes of the curves change. Therefore, it seems that an exponentially decaying function does not adequately define the two modes of subsidence actually having occurred.

In both instances (a lag time of 4000 and 10 000 days), the curves shift in a nearly identical manner and therefore, it is expected that this would occur for any value lying between these. The actual value for the lag time characteristic of CCP is not known, however, as no indication of the completion of subsidence due to pillar creep was observed between the years 1970 to 1983.

Another phenomenon regarding subsidence at CCP is also of interest. Figures 10 and 11 indicate that no subsidence had occurred over line #1 until 1980 even though mining had begun in the mid-1970's. There is no such allowance in SPASID and consequently subsidence is assumed to begin immediately upon extraction.

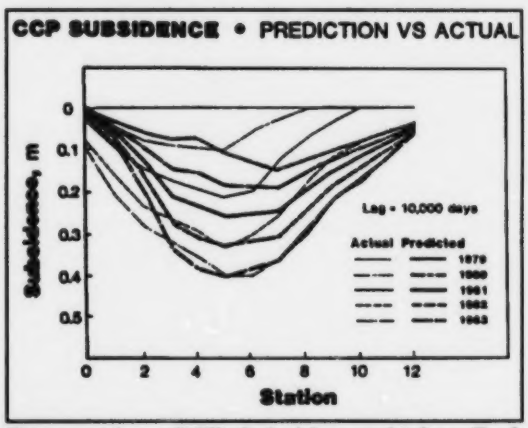

Figure 10 : CCP Subsidence [After Ref. 13]

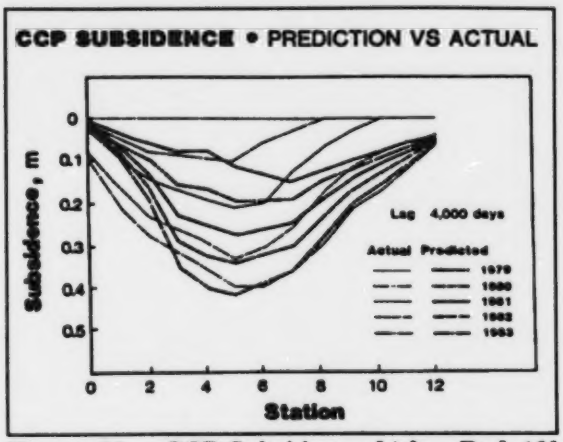

Figure 11 : CCP Subsidence [After Ref. 13]

Table 3 outlines some of the advantages and disadvantages of SPASID for subsidence prediction.

Table III : Advantages and Disadvantages of SPASID

ADVANTAGES	DISADVANTAGES
- comprehensive - both longwall and room and pillar mining methods can be simulated. - system identification of site and subsidence parameters	- subsidence is based on extracted volumes alone - no allowance for the initial delay in subsidence observed at CCP, line #1. - interactive mode is not very user friendly.

5. PREDICTIVE HYPSOMETRY INCORPORATING LAG (PHIL)

As highlighted in chapters 3 and 4, the zone area method of subsidence prediction resulted in good agreement with actual data for potash mining and the structure of SPASID was recognized as being ideally suited to act as the frame work to develop a model.

The transfer of SPASID from the main frame environment to the Personal Computer (PC) permitted a restructuring of the program modules, an improvement in the program's user friendliness, and a change in the prediction algorithm.

The PHIL program consists of seven modules; configure system, the user interface, the preprocessor, the subsidence module, the post processor, the printer and plotter modules. These modules use seven data files, two system configuration files, and can produce multiformat output files (see user manual).

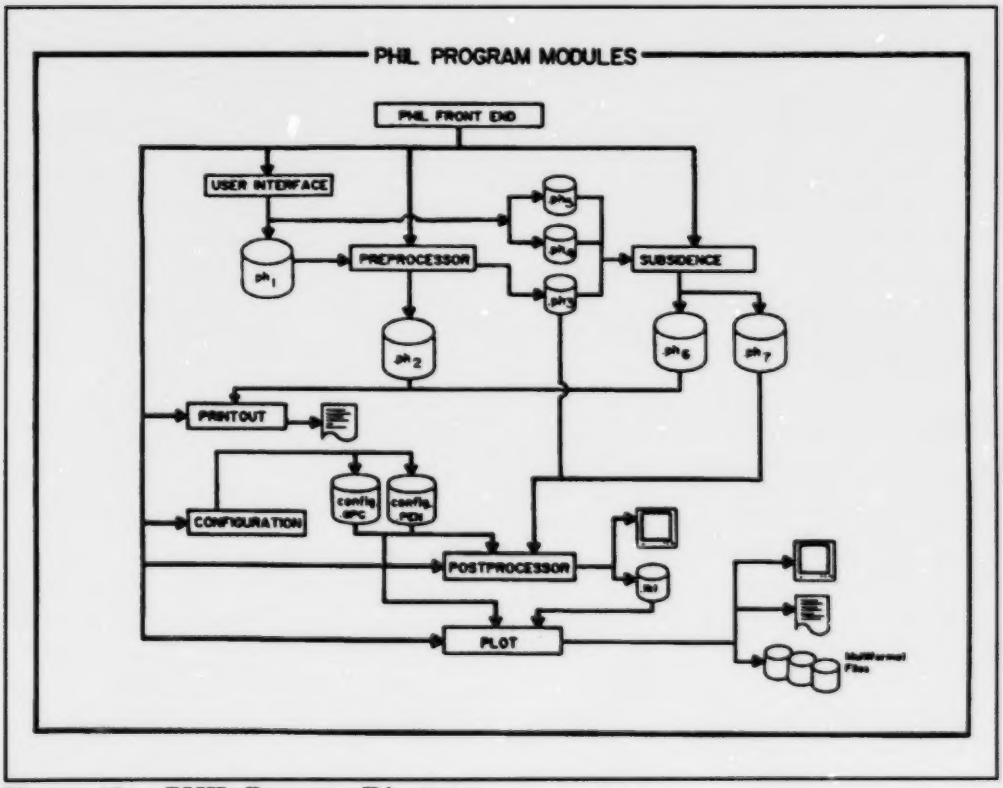

Figure 12 : PHIL Program Diagram

The association between modules and files is shown in Figure 12. All files are outlined in the user's manual. The program is designed to run on an IBM PC-XT compatible computer equipped with a hard disk. It is recommended that the computer have a math co-processor. DOS 3.0 or a more recent version of DOS is required to run PHIL.

The user interface allows the user to input the information that is required for the simulation. It combines all of the commands that the user will need to use the PHIL package, and creates the control files for the preprocessor and the subsidence modules. Mine and surface geometries along with the prediction algorithm's parameters are defined.

The preprocessor and the subsidence modules process the command files that are produced by the user interface in order to calculate predicted subsidence. All of the computations are carried out within these two modules.

The preprocessor formats the user's information into an array to be used by the subsidence module. The array contains the mine and surface geometries along with the simulation parameters defined in the user interface. Prediction of subsidence is done using the zone area method. The subsidence module can optimize the six subsidence prediction parameters used in the algorithm by using the simplex numerical technique. The predicted subsidence data is contained in an array which can then be used by the post processor.

The source code for all modules is included in Appendix A.

In order to start building mine and surface grids, which is the input required to run PHIL, the user need only define:

- mining geometry and extraction schedules,
- bench mark locations with optional elevations (can be set to zero if a uniform dataform plane is desired),
- depth of cover for each benchmark.

This is entered into the program via the user-interface. The preprocessor contains the extrapolation routines required to interpret all remaining information needed by the subsidence module. If the user wishes to optimize the site specific parameters, actual and measured subsidence must also be entered. These parameters can be left at their values or manually altered by the user. Section 5.2 outlines how this information is entered.

Data can be entered with SI or imperial units but must be either one or the other. Simulation results will be of the same unit set.

5.1 PHIL's Front End

In order to easily access the seven modules of PHIL (configure system, user interface, preprocessor, subsidence module, post processor, print module, and plotter module), a front end program written in "C" language was developed. The front end allows the user to access any one of these modules under one shell. The structure of the program is given in Figure 13.

As shown, the front end, enables the user to interactively access the above mentioned modules of PHIL.

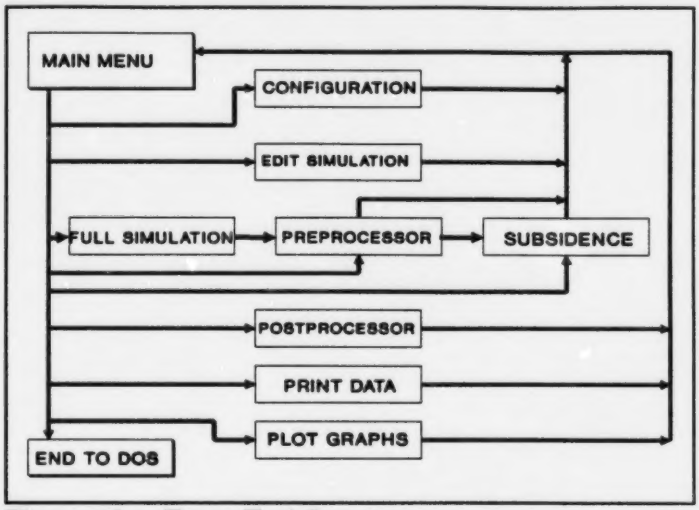

Figure 13 : Front End Structure

When the editing option is chosen, the user interface is loaded. The user can now edit all input parameters required to run a new simulation. Once out of the user interface and back to the front end program, either the executable for the preprocessor or the subsidence modules can be run independently. If only subsidence information is modified, it is only necessary to run the subsidence module to get modified subsidence predictions.

Other front end options are detailed in the user's manual.

5.2 The User-Interface (Edit Simulation)

The user interface is a window oriented input interface that produces the command files for the preprocessor and the subsidence modules which are accessed via the front end. Using windows, it is possible for the user to modify any parameter that is used in the simulation. Because the user interface is based on a windowing paradigm, the user can select the parameters that require modification without having to see all of the other data that is used in the simulation.

All of the simulation data that is entered by the user is processed and sent to two command files, ".PH1" and ".PH4" (Figure 12), when the user saves the input. These files control the execution of the preprocessor and subsidence modules,

using a series of internal commands. Since the user interface takes care of the command syntax the user can concentrate on properly setting up the simulation. During execution, the user interface uses a series of temporary files to store all the parameters that have been entered by the user. All of the temporary files use the ".PHL" extension. During normal operation, these files are removed from the disk at the end of a simulation. However if there is a problem (i.e. power failure, brown-out...), these files will remain on disk and should be removed from the disk before using the user interface for a new simulation. A hard disk greatly increases the execution speed of the PHIL program, since the ".PHL" files are continuously being modified during an editing session.

Within the user interface, the user is presented with two types of input forms. The most commonly used input form is the information prompt window. This window presents the user with a given number of cells that he must complete. The user may move between the cells using the computer's cursor pad, thus controlling which data should be changed.

Figure 14 gives an example of the window used to input the cutheight. The user must first enter the mine grid number. Once this is done the program updates the minimum and maximum values on the screen, allowing the user to modify the values.

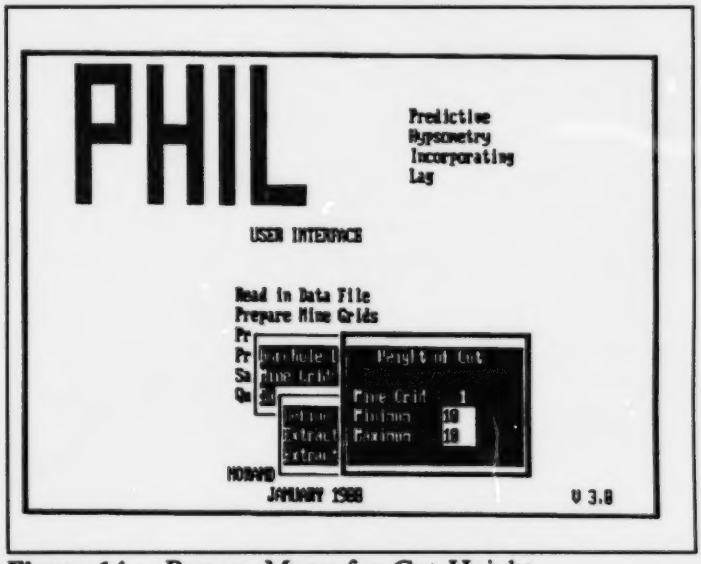

Figure 14 : Pop-up Menu for Cut Height

A second type of input window is the tabular input form (TIF). This form is used to input tables of values such as drillhole data, actual measured subsidence and dates of extraction. Figure 15 illustrates the TIF for drillhole data. The user can either input information in the TIF or use the "import" function to call in a file that has been produced by a spreadsheet program (details are given in the manual). The number of columns in a TIF is predefined, as is each column's title. The maximum number of rows in a TIF is 250.

Figure 16 shows the main user interface screen. It contains six main functions that the user can perform. These functions allow the user to read information from a previous simulation, modify information for the preprocessor, modify information for the subsidence module, determine the amount of information that should be printed in the report files, save the simulation data to disk and exit to DOS.

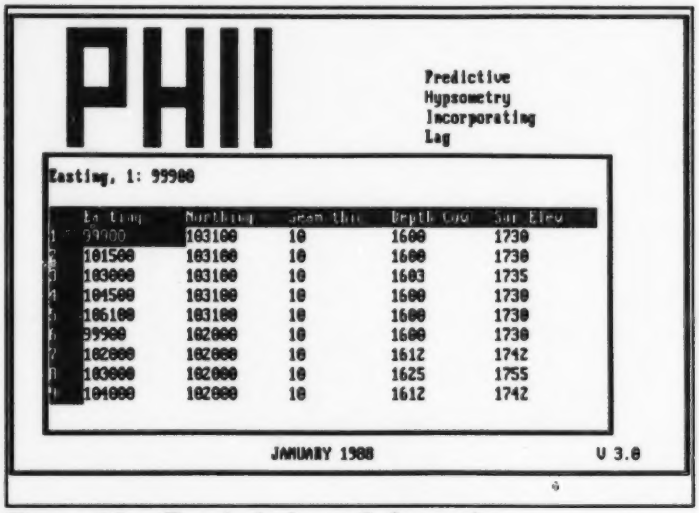

Figure 15 : Borehole input Information

5.2.1 Read in data files

This first option is used when minor changes must be made to a previously executed simulation. The program reads in old simulation information, from a specified file, prepares all temporary files and fills the computers internal variable list. This option allows the user to make fast changes without having to re-enter all of the simulation data.

5.2.2 Prepare Mine and Surface Grids

The second option allows input of all data that is required by the preprocessor. The first information that is entered is the drillhole data. The drillhole data is used to define the location and the limits of the ore body as well as the surface topography. Once the ore body is outlined, the user then builds the mine model by defining mining grids. Each grid is identified by a grid number and size of cells defined along the local easting and northing. A mine grid can be defined in four different ways. In each case, a different corner of the grid is selected as an origin. Choosing different origins affects the value of the azimuth and the numbering of the cells within the grid.

Figure 17 illustrates a sample mining grid. The sample grid is a 2 x 6 matrix of mining cells. The dimension of each cell is arbitrarily set at 50 x 10 meters. Thus, the total dimension of the grid is 100 x 60 meters. Each corner of the grid is identified by a letter for easy reference. To place the grid in space, assume that the line AB has an azimuth of 45°, and the coordinate system originates at A.

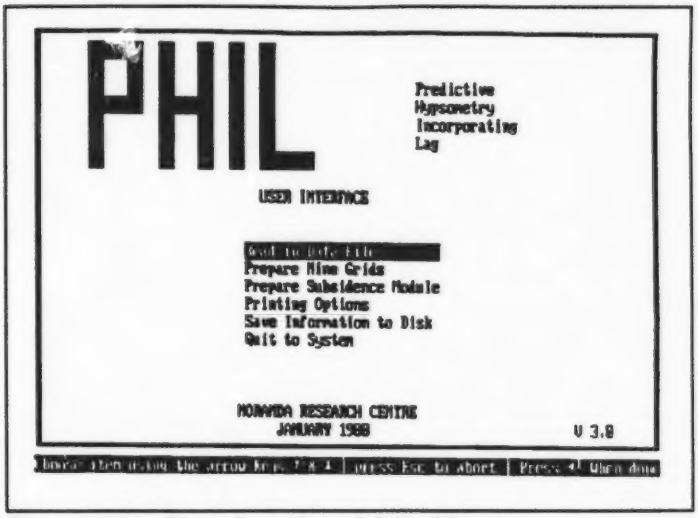

Figure 16 : User Interface Main Menu

Using point A as an origin, sets the starting coordinates of the mine grid at (0,0). In order to determine the corresponding azimuth find the lines which intersect at point A. These lines are AB and AD. Referring to the figure, AB has an azimuth of 45° and AD has an azimuth of 135°. The correct azimuth of the grid is the one where the arrow representing the azimuth angle strikes the outside of AB, thus intersecting the azimuth for a grid originating at A has an azimuth of 45°.

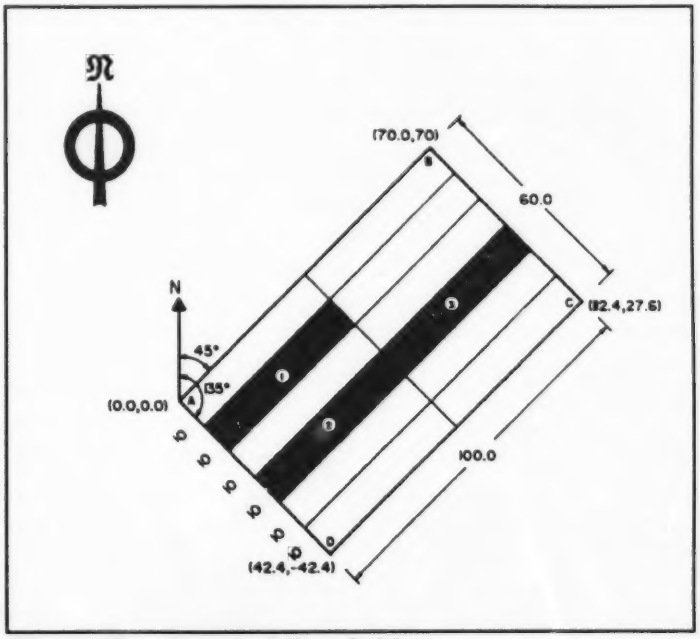

Figure 17 : Sample Mine Grid

Therefore, if point D were to be defined as the origin, the above rule would result in an azimuth of 315°. The first line intersection would be DC, however, the intersection would

occur from the inside edge. Therefore, this would be rejected and the line DA selected instead.

Since the azimuth is known, local north and local east for the mine grid can be defined. Local north is always in the direction of the line that was used to find azimuth. Local east is 90° rotated clockwise, or along the line that was rejected in defining the azimuth. The local easting and northing are used to define the number of cells within the grid. Using point A as the origin, it defines six, ten meter wide cells along the local east line, and two, fifty meter cells along the local north line. Table 4 gives the grid definition using each of the corners as an origin.

Table IV : Various Mine Grid Captions

ORIGIN POINT	COORDINATES		AZIMUTH	EAST		NORTH	
	EASTING	NORTHING		# OF CELLS	DIMENSION	# OF CELLS	DIMENSION
A	0	0	45	6	10	2	50
B	0	70	135	2	50	6	10
C	112.4	27.6	225	6	10	2	50
D	42.4	-42.4	315	2	50	6	10

The next step is to define the amount of material that is removed. The cut height can either be kept constant for the grid, or a maximum and a minimum cut height can be defined. Unlike SPASID whose influence functions are based on volumes extracted, PHIL uses the zone area method. Therefore, subsidence is a function of the area extracted and which zone it has been extracted from. Consequently, the cut height is not critical in the subsidence calculation. A constant cut height can be specified by simply inputting the same value for the minimum and maximum. Entering two different numbers will ensure that even though the potash zone may be narrower than the minimum or thicker than the maximum, mining constraints are respected and only plays a role in the display of some of the graphical features of the program.

Once mine grids are defined, the extraction dates (when the potash was mined) for each cell must be given. When entering extraction dates, it is important to choose a unit of time that will be used. Once chosen, this time unit is then used throughout the remainder of the simulation. Valid time units can be years,

months, weeks or days. However, the time interval shown in Figure 18 must be defined so that the resultant unit is equivalent to a whole time period, a year in the example.

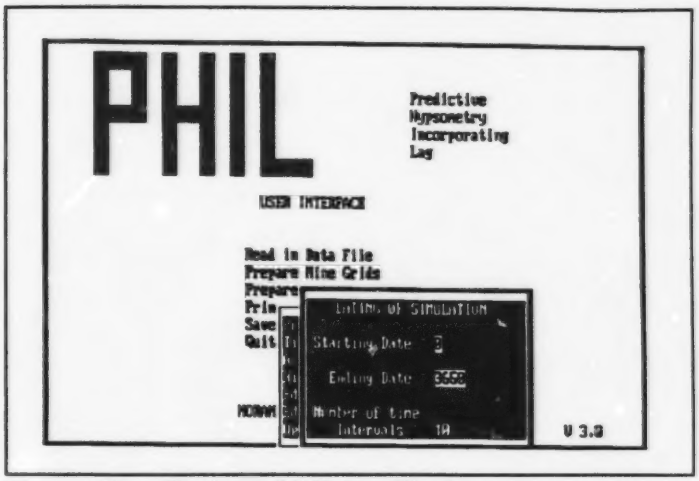

Figure 18 : Dating of Mining Blocks

Each cell that is extracted must be separately dated. The user interface, using a TIF, allows the user to date up to 250 cells for each defined mining grid. To enter an extraction date, the coordinates of the cells are based on the local easting and local northing. Using Figure 17, assuming that point A is the origin of the grid, and that all blocks are removed on the 20th month, the extraction information for the cells is given in the table below.

Table V : Dating of Mining Grid Cells

	E. CELL #	N. CELL #	DATE
1	2	1	20
2	4	1	20
3	4	2	20

Any cell that is not explicitly dated by the user is not removed during the simulation and therefore, represents a pillar.

Once the mined area is defined, the location of the benchmarks must be given.

Benchmarks can be either be entered as individual points or a series of benchmarks can be placed along a line. In both cases benchmarks are entered using a TIF (Figure 19) in the user interface. The information that is required when defining a line of benchmarks is the X and Y coordinates (given as global coordinates), the azimuth of the line, the number of points on the line and the distance between each benchmark. If a single benchmark is to be entered then the azimuth, the number of points and the distance must be set to zero.

For an XY plot of actual and calculated subsidence, the postprocessor will project a set of selected benchmarks onto a user defined line. A cross-sectional view along the defined line is then produced. These plots are scaled and allow the user to see the amount of subsidence that has occurred.

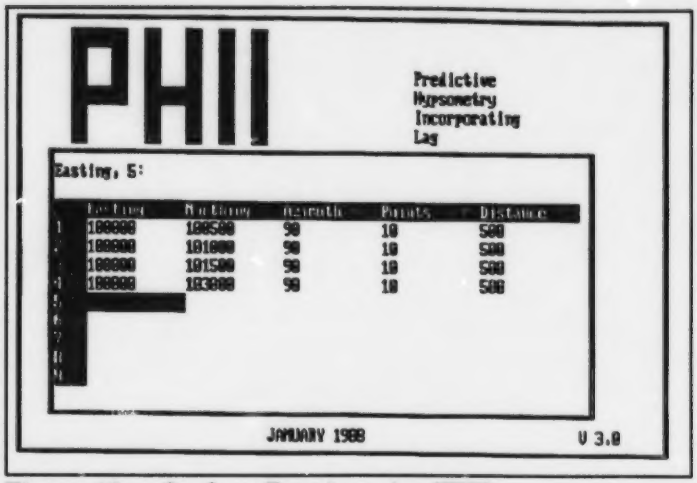

Figure 19 : Surface Benchmarks (TIF)

If optimization is used then all benchmarks that are used must have associated actual measurements. Benchmarks that do not have a complete history of subsidence data, or benchmarks whose data is questionable should not be used during optimization.

5.2.3 Prepare Subsidence Module

In order to prepare for a simulation, the command file, ".PH4" has to be created and loaded as explained earlier. This is done via the user interface. Once the "Prepare Subsidence Module" option has been selected, seven sub-options become available to the user. These all deal with the initializing of the computational parameters used in the prediction or inputting actual measurements when optimization is required.

For more details, refer to the user's manual supplied with the program.

5.2.4 Printer Options

The user interface allows the user to specify what information will be contained in the output file. Therefore:

- input data,
- extraction dates,
- mine grid information,
- surface grid information,
- displacement data.

may be either toggled on or off.

5.2.5 Save information to disk

Once all of the simulation information has been entered, the user may save this data. The program prompts the user to specify a directory and a filename as well as a four line description of the simulation using the temporary ".PHL" files and data that is stored in dynamic memory arrays. The user interface produces the files that are required to run the preprocessor, the subsidence modules, and the postprocessor. This option does not return control to DOS.

5.2.6 Quit to System

Once the data is saved, the user can exit to DOS. The program will warn the user if the data has not been saved before exiting. If the decision to exit is taken, the program performs house keeping by removing all the temporary files from the hard disk, and by clearing memory before returning control to DOS.

5.3 Preprocessor

The preprocessing module is used to:

- create a data storage array (mine and surface geometries and extraction dates) which is used by the subsidence prediction module,
- interpolate the user inputted drillhole information to the specified benchmark locations,
- create an output file for user verification.

The preprocessor performs all of its calculations based on the data that is supplied from the user interface. Once the data is processed and the preprocessor receives the TERMINATE command, the data array is stored in a binary data file that is passed to the subsidence module. After closing the data file, the preprocessor returns control to the operating system. Figure 20 shows a flow diagram of the preprocessor module.

5.3.1 Interpolation Routines

In PHIL, drillhole data is used to define the topography of the potash zone and surface. From surface elevations, the elevation at another point is found using a quadratic approximation. Therefore, at least six data points are required in order to define the six coefficients in an equation which has the form:

$$Z = a_1 + a_2X + a_3Y + a_4X^2 + a_5Y^2 + a_6XY$$

Where, Z : elevation
X,Y : distance between drillholes
a_n : weighting coefficients

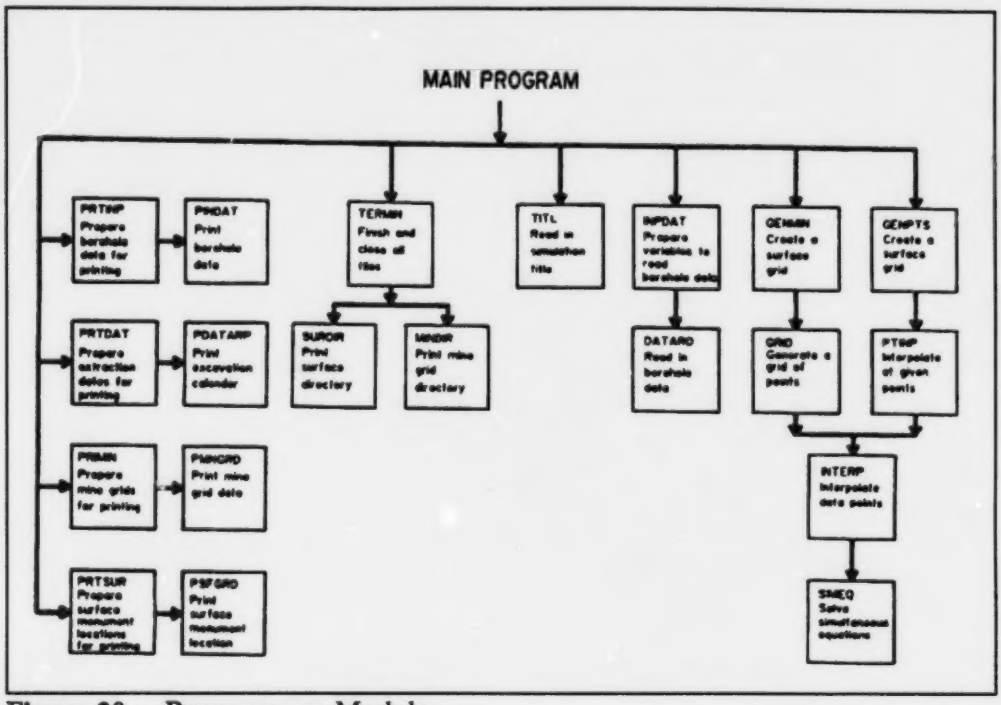

Figure 20 : Preprocessor Module

The location of the mine grids must be defined in such a way to assure that they are located within the perimeter created by the outermost drillholes. If this is not done, the interpolation subroutines will not be able to properly determine the topography of the horizon. If drillhole data does not actually physically exist, the user must define similar data from surface elevations and underground surveying results. The routines require at least eight data points: the more points, the better the fit will be.

5.3.2 Printing Routines

Four printing subroutines send information to the output file. The command file created by the user interface determines the amount of information that is reported.

5.3.3 Terminate Routines

Once all of the data is processed the command file sends the TERMINATE command. This command causes the preprocessor to open a binary data file and to process the mine and surface grid directories. The directories are then sent to the binary data file, temporary files are removed and control is returned to the operating system.

5.3.4 Memory Allocation

A function of the preprocessor is to define mine and surface geometries as well as the extraction schedule of the mine grids themselves. This information is stored in one data array as shown in Figure 21. How the individual sections of

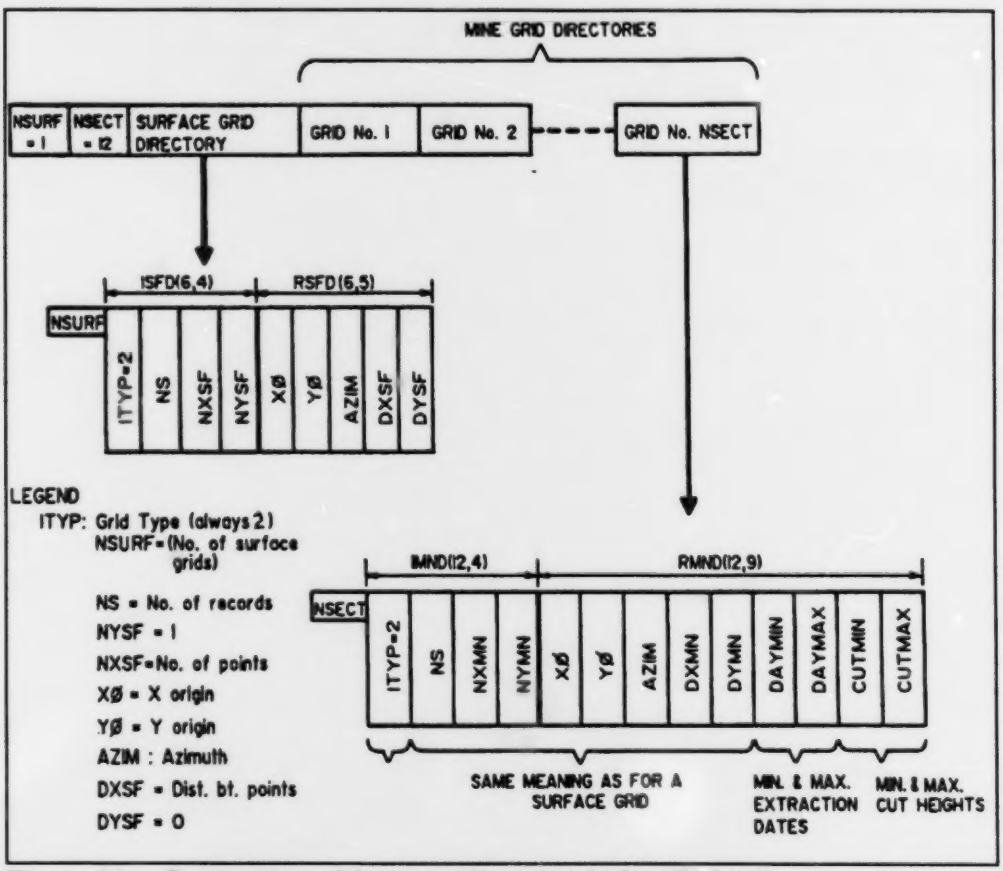

Figure 21 : Preprocessor Memory Allocation [After Ref. 14]

the array are subdivided is also given. This data structure remains unchanged from the original SPASID program.

Once the drillhole information is input as outlined in Section 5.2, the interpolation routine is used to interpolate the field data to the benchmarks defined by the user. Therefore, the drillhole data will represent the original elevations at the benchmark locations. The surface data base memory structure is given in Figure 22.

A mine data base is also organized by the preprocessor. The interpolation routines are also used to interpolate values from the drillhole data, e.g. mining zone thickness, bottom elavation and the depth of cover. The structure of this data base is given in Figure 23.

This information is then passed to the subsidence module in the binary ".PH3" file.

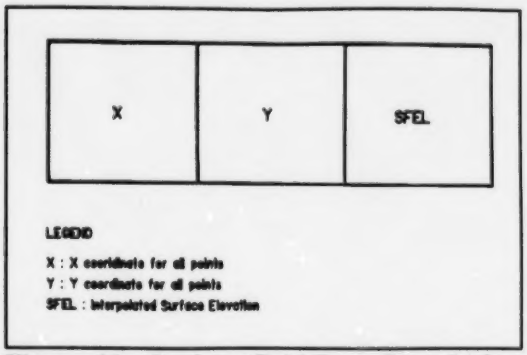

Figure 22 : Surface Grid Data Base [After Ref. 14]

5.4 Subsidence Prediction Module

With the data (.PH3 file) and instructions (.PH4 file) passed from the preprocessing module, the subsidence prediction module is used to calculate expected subsidence based on the zone area method, a simplified influence function technique. The module also contains an optimizing routine for the six parameters used in the subsidence computation. The program structure is shown in Figure 24.

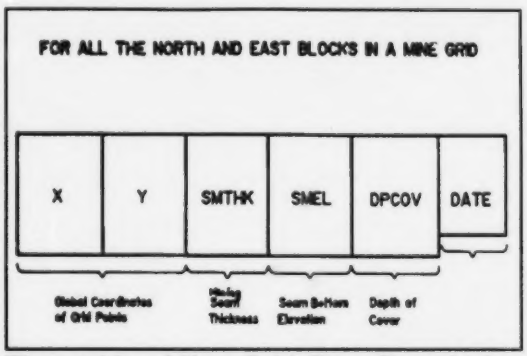

Figure 23 : Mine Grid Data Base [After Ref. 14]

5.4.1 Prediction Algorithm

Steed et al (1) showed that the zone area method for predicting subsidence gave good correlation to actual measurements taken over several potash mines. An example of the fit is snown in Figure 6. It was noted that subsidence occurred in two phases resulting from a relatively rapid convergence of the back to the floor followed by a longer term subsidence component due to pillar creep. The two governing equations respectively take the form of:

$$S = mX$$

and

$$S = mX + b$$

where S : subsidence rate
X : percent extraction.

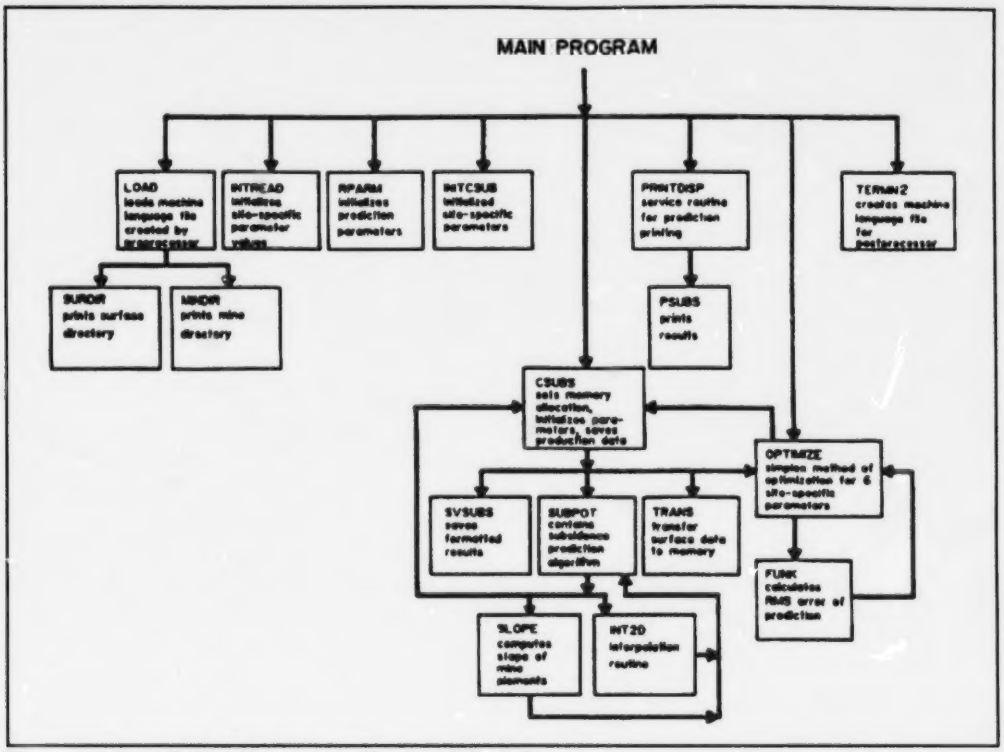

Figure 24 : Subsidence prediction Module

Therefore, the slope of the curves and the Y intercept may change from operation to operation. An investigation of subsidence and the rate of subsidence versus extraction at CCP found once mining was out of the zone of influence of an overlying subsidence benchmark, the rate of subsidence was remarkably constant. These results are shown in Figure 5 and represent the creep component of overall subsidence. The work also noted that there is a time lag between the beginning of mining and when subsidence started to occur on surface. This was therefore incorporated into the algorithm and varied from site to site.

The algorithm defined in this initial work implies that once subsidence becomes a function of pillar creep, it continues at this rate forever. This obviously makes no physical sense, however, it seemed to model conditions well at the time. In PHIL, two other parameters were incorporated to account for full closure and hence, the halting of surface subsidence. An exponential decay of the subsidence rate was incorporated but because of the work by Steed et al, a second lag was defined. This lag is used to define the number of years constant subsidence can be expected. Once this condition has been satisfied, it is assumed that the te will decay by:

$$S = s_0(e^{-kt})$$

where,

S	:	subsidence at time t
s_0	:	initial subsidence rate
k	:	exponential constant
t	:	time.

Having initially incorporated the algorithm proposed by Steed et al (1), it was found, as can be determined by inspection of Figure 5, that for extractions below approximately 12%, the constant subsidence rate could be negative (this minimum percent extraction is user defined). Therefore depending on the magnitude of subsidence resulting from rapid convergence of the back and floor and the number of years extraction remained below 12% in the zone of influence, total subsidence could be negative. In other words, uplift was occurring. This was corrected for in the PHIL model.

The resulting algorithm used in PHIL yields a subsidence rate profile as outlined in Figure 25.

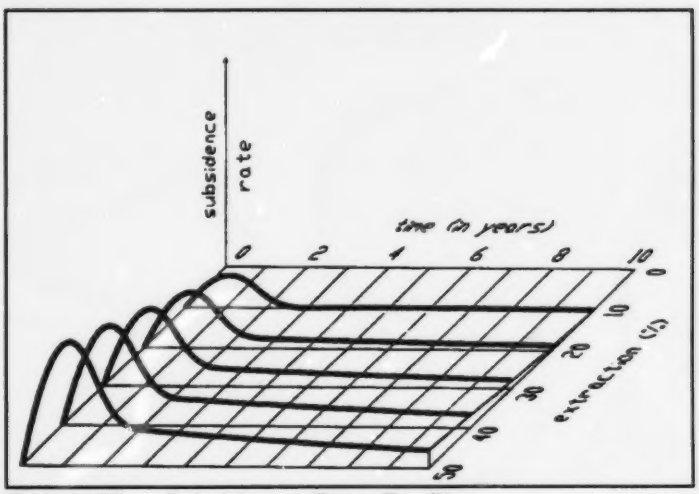

Figure 25 : Subsidence Rate Profile

In programming the algorithm, it was essential to keep track of the date an element was mined as preset by the preprocessor. If the element hasn't been mined before the year subsidence is being calculated for, then it must be ignored in the analysis. An even more complicated accounting of the dates of extraction had to be used so that the proper component (due to rapid convergence, constant creep, or decaying creep) of subsidence could be applied.

The algorithm also employs an edge effect, if so specified by the user. The edge effect acts to reduce the elemental size of cells extracted within a specified distance of any large pillar. The user need only enter , through the windowing routines, the northing and easting of the pillars which will affect subsidence. The subroutine will then determine whether an element is within the specified zone of influence and weight the extracted element according to the following

exponential function:

$$\text{Weighted Area} = \text{Area} * \text{Exp}\left[\frac{-c_1}{[\text{Dist}]}\right]$$

Where,

Area : the unit area of element
c_1 : user defined constant
Dist : user defined zone of influence

If the user feels that a pillar will act to decrease the amount of subsidence manifested on surface say 100 m into the workings, Dist would be set to 100 in the above equation. In PHIL, this reduction in expected subsidence near large pillars is called the edge effect and results in the characteristic trough associated with subsidence over Saskatchewan potash mines. As c_1 approaches zero, the edge effect has little influence on the subsidence over the nearby workings.

5.4.2 Optimizing Routine

The prediction algorithm used in PHIL incorporates six fundamental parameters:

m1 : slope of the extraction function defining initial subsidence,

lag1 : represents the time delay witnessed before any subsidence is noticed,

m2 : the slope of the extraction function defining long term subsidence (due to creep),

b1 : the Y intercept of the long term subsidence function,

lag2 : the number of years the long term subsidence rate remains constant,

k1 : constant for exponential decay of the long term subsidence rate.

In order to optimize these site specific parameters, a routine was written. This routine incorporates the simplex method of optimization and is represented in Figure 26. Reference 15 outlines this method in detail. There are three parameters and for the sake of illustration, they can be considered to be part of the arbitrary function:

$$Y_{predicted} = \frac{P_1 X + P_3}{P_2}$$

Therefore, on Figure 26, E'_1 through E'_4 represent the RMS error between $Y_{predicted}$ and a set of actual results where:

$$RMS_{error} = \frac{\sqrt{(Y_{predicted} - Y_{actual})^2}}{\#\ of\ data\ points}$$

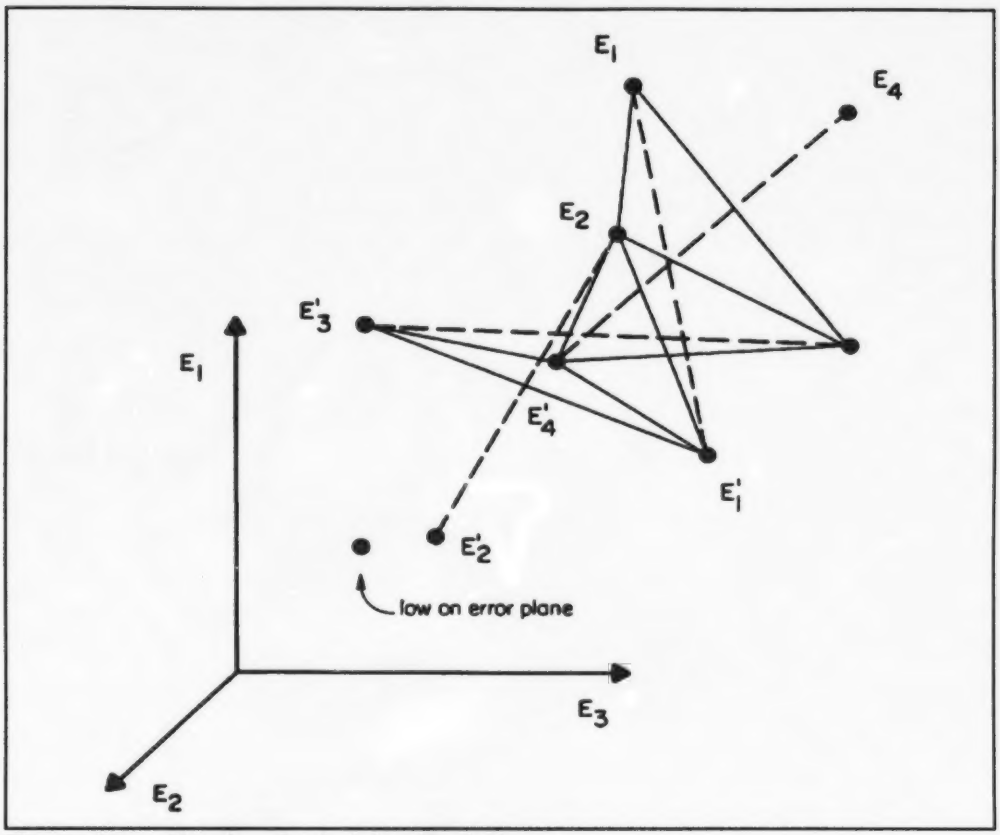

Figure 26 : Simplex Optimizing Technique

Therefore, through the iterative simplex technique, the parametric values associated with E'_2 (the near low on the error plane) would be returned as having given the best results even though this is not the true low as indicated in Figure 26. It is within the defined tolerance.

Associated with each of the errors are the individual parametric values. The actual results can then be used to calibrate the prediction function using the simplex method. In essence, this technique searches for the lowest RMS error associated with the parameters. As with any numerical technique, it is possible

to find unrealistic parametric values. In this case, a new starting point should be used and the routine rerun. The optimizing routine in PHIL is programmed for this particular model and, therefore, only six parameters can be optimized. A flow chart of the simplex technique is given in Figure 27.

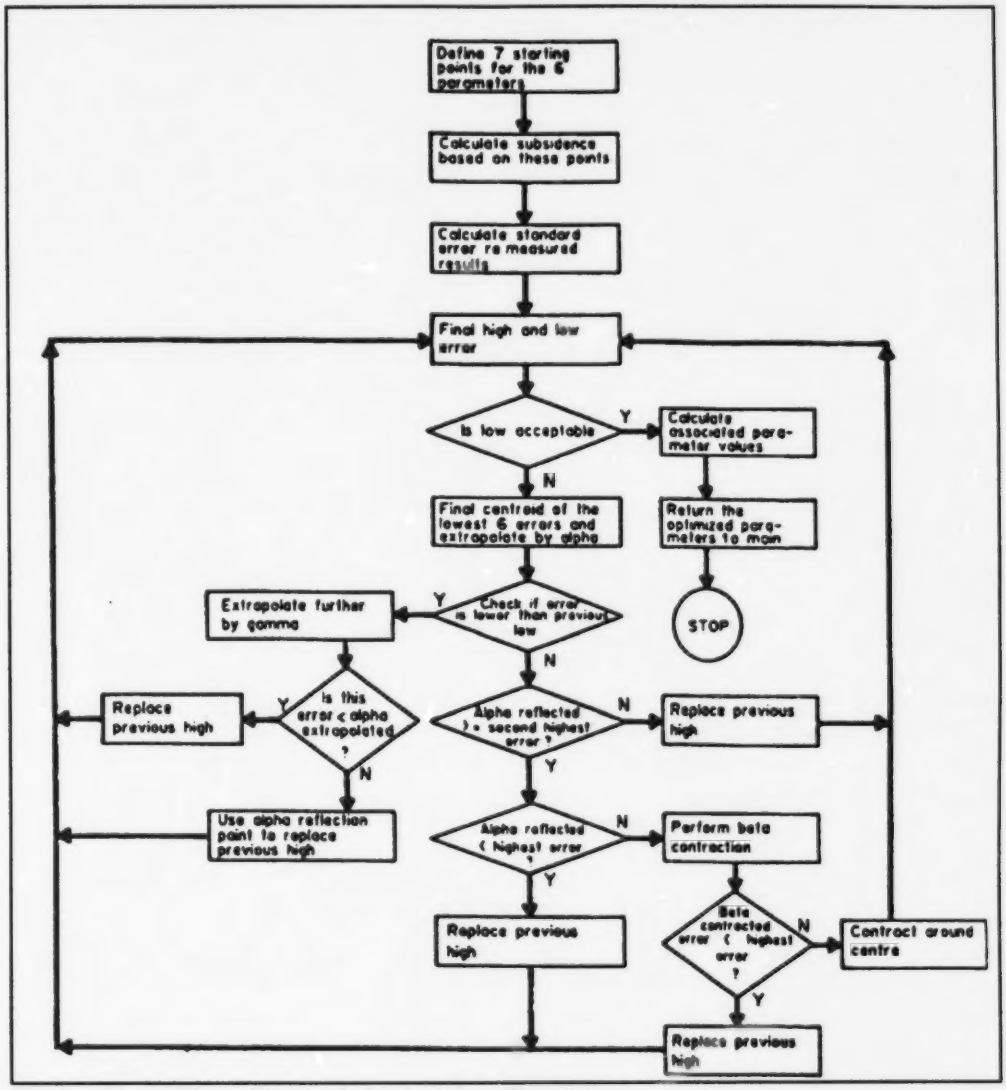
Define 7 starting points for the 6 parameters
Calculate subsidence based on these points
Calculate standard error re measured results
Final high and low error
Is low acceptable
Y
N
Calculate associated parameter values
Return the optimized parameters to main
STOP
Final centroid of the lowest 6 errors and extrapolate by alpha
Check if error is lower than previous low
Extrapolate further by gamma
Is this error < alpha extrapolated ?
Replace previous high
Alpha reflected) = second highest error ?
Replace previous high
Use alpha reflection point to replace previous high
Alpha reflected < highest error ?
Perform beta contraction
Replace previous high
Beta contracted error < highest error ?
Contract around centre
Replace previous high

Figure 27 : Flow Chart of Optimizing Routine

In PHIL, the simplex method of optimization first defines seven points on the error function plane as defined by the RMS error of the predicted subsidence versus measured subsidence. These points individually define a group of the six prediction parameters. These are then passed to a subroutine which calculates the subsidence associated with seven groups of parametric values and compares the predicted subsidence to actual data to find the RMS error. Time periods where both predicted and actual subsidence are zero are not included in the analysis as this would bias the RMS error heavily toward zero.

Once the errors associated with the seven parametric groups have been defined, the highest of these is ignored and the centroid of the others is found. A new point on the error plane is then found by extrapolating through the centroid. The error of this new point is found via defining the parametric values and recalculating subsidence. Depending on the outcome of the error calculation, the extrapolation may be increased or contracted to find an even lower value. Once the lowest of the three has been found, the whole process is reiterated until the difference between successive lows on the error plane are within a hard coded tolerance or the error associated with a group of parametric values is below some user defined limit. Hence, the iterative movement of the simplex to the low on the error plane will return six optimized parameters to the main program. This process is illustrated in Figure 26 for the optimization of three parameters.

5.4.3 Memory Allocation

The subsidence prediction module of PHIL creates a data array which contains:

- a subsidence grid directory,
- the subsidence data base.

These are used by the postprocessor to create plots of the calculated information and also to generate output files. The structure of the data is shown in Figure 28.

5.5 Postprocessor

PHIL's postprocessor uses GRAPHIC^{tm} graphic libraries to produce:

- xy plots of predicted and/or actual subsidence,
- mine grid plots including extraction schedules,
- contour plots of subsidence or the subsided surface,
- composite plots

The plots can be viewed and plotted individually or combined up to four on a page. The structure of the program is given in Figure 29. In order to use the postprocessor, the execution of both the preprocessor and the subsidence module have to have been successfully completed. If any of the data files that are produced by the preprocessor or the subsidence module are missing the

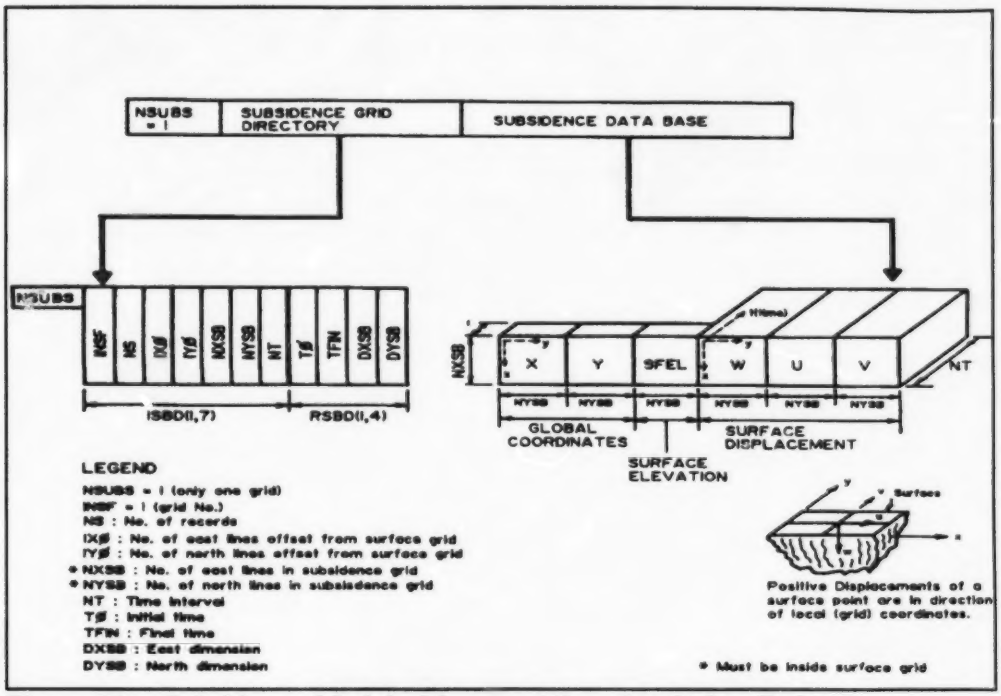

Figure 28 : Subsidence Module Memory Allocation [After Ref. 14]

postprocessor will not execute properly.

The first step in using the postprocessor is to select the configuration and the data files that are to be used. Once this is done the postprocessor reads in all of the data into RAM. The configuration file is used to control the appearance of the graphs that are produced by the postprocessor. A complete description of the postprocessor is given in the user manual appended to this report.

Once the information is read from the data files and stored in the computer's memory it is possible for the user to construct the plots. It should be noted that the postprocessor is not used to print the actual plots. The postprocessor creates a plot file, this plot file can then be sent to an output device using the plot program.

An overview of the plot options will be given in this report. For a complete description of the available features refer to the PHIL user manual.

5.5.1 XY Plots

The XY plot is primarily used to plot the benchmark subsidence, either real or predicted. The plots that are created are subsidence versus projected distance between benchmarks. Using the menus, the user may choose a series of benchmarks that he wants to plot from those that have been modeled.

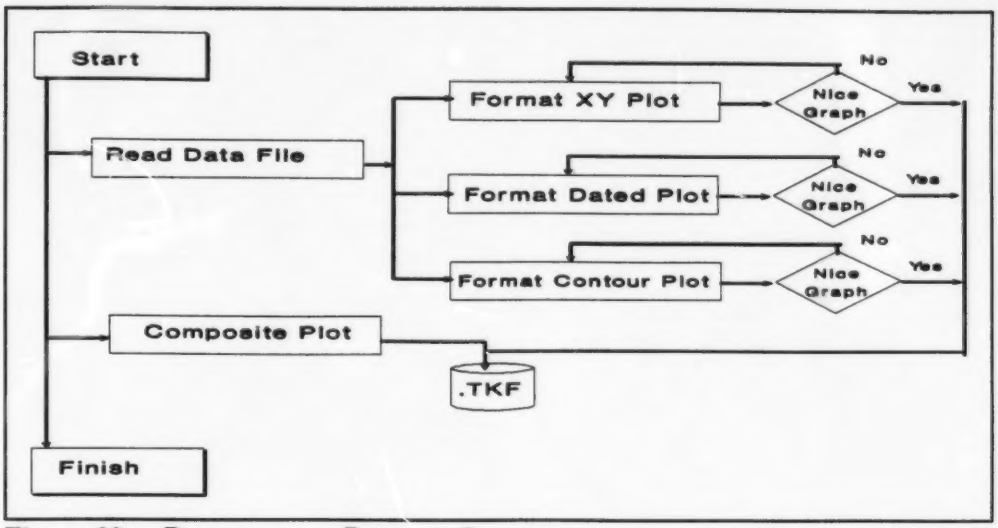

Figure 29 : Postprocessor Program Structure

The selected benchmarks are then projected onto a straight line (see user manual for details) which is then used as the distance axis (X axis of the plot). The subsidence data for each of the benchmarks is used as the Y axis data.

Once the benchmarks have been selected the user may select the time period for which subsidence is to be plotted. Up to eight lines may be plotted on a single graph. Each line on the graph may represent real or calculated subsidence for any time period that has been simulated.

Menu options are also available to change the colours of the graph, the positioning and the contents of the legend, as well as the limits on the axes. Before the plot is sent to a graph file, the graph can first be viewed on the computer monitor.

5.5.2 Dated Extraction Plots

The dated extraction plot allows the user to verify the geometry of the simulated mining cells and the location of the benchmarks. The plot that is produced is a plan view of the modelled mining grids, underlying the location of the benchmarks.

Using the menu options the user may also specify a time period. Once the time period is entered the program will highlight all of the cells that have been removed up to this specified time period. This plot should be used with the contour plot to produce a comprehensive plot of the simulation results.

5.5.3 Contour Plots

Using this plot the user may produce a contour plot of the subsided surface or of subsidence. The user may select the extents and the time period of the plot, as well as the colour options for the plot. The user may also display the location of the benchmarks on the contour plot.

One of the most important options in the contour plotting routine is the selection of the contouring interval. The selection of the interval will determine wether the contouring package will perform properly or if it will fail. The PHIL user manual outlines the selection criterion that is used for the contouring intervals.

5.5.4 Composite Plots

Composite plots can include all of the aforementioned plots or any combination of them. The program retrieves the necessary plotting files created in the plotting routines and adjust these files so that those specified by the user fit on one page. Hence, a new plotting file is generated.

Figure 30 is a composite plot of all three types of plots available.

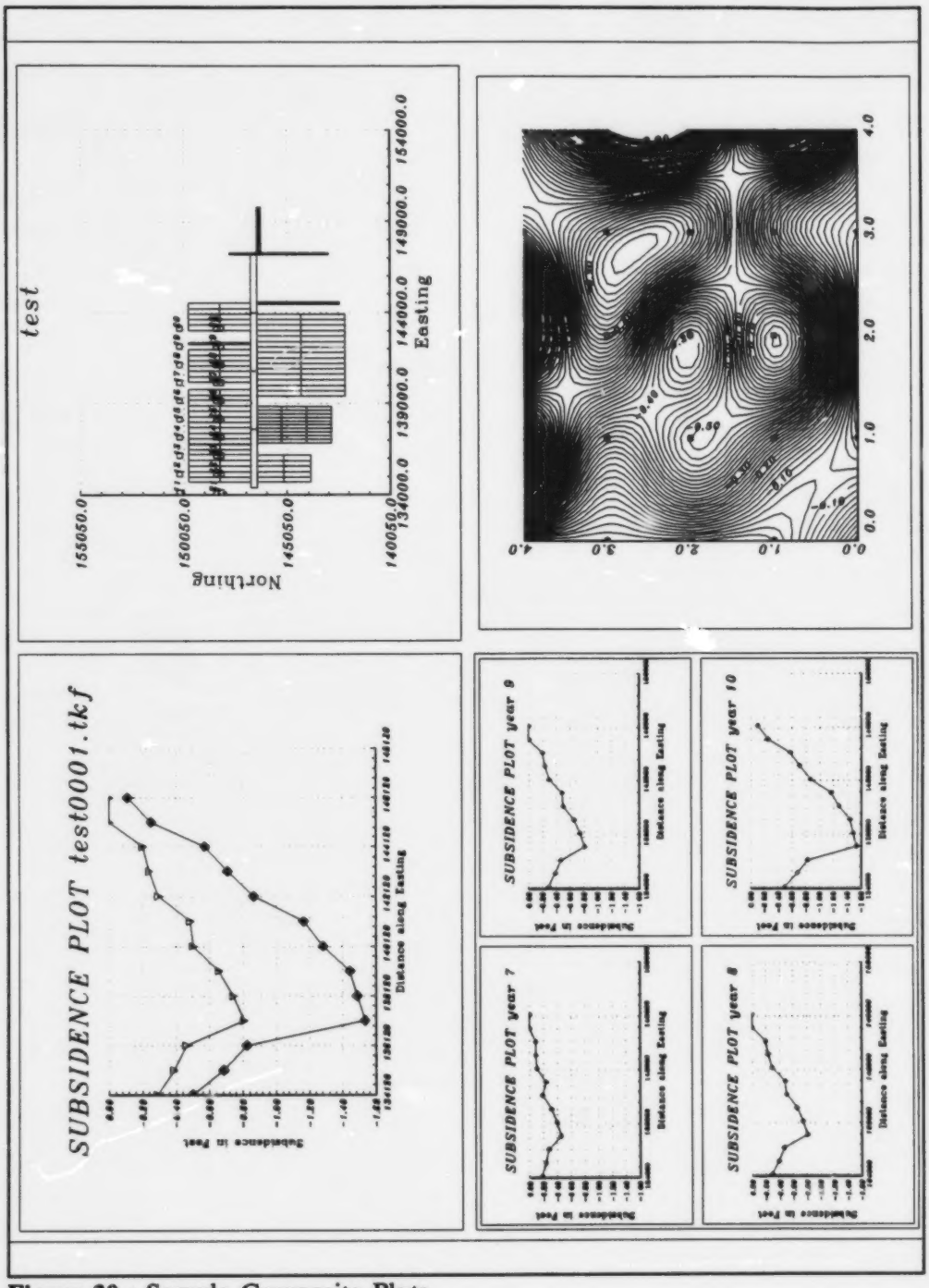

Figure 30 : Sample Composite Plots

6. CALIBRATION OF PHIL

In order to verify the accuracy of the prediction algorithm incorporated into PHIL, two mines were modelled. These mines were CCP (Block II) and the K2 mine belonging to IMCC. The results are presented below.

6.1 CCP

A line of 13 subsidence stations overlying Block II of the CCP mine was selected for calibration purposes. The default parameters are shown in Figure 31.

These parameters gave poor correlation to measured subsidence data as indicated in Figure 34. However, running the model through the optimizing routine and employing the edge effect improved the fit as shown in the same figure. The RMS error between measured and predicted subsidence for the 10-year period (1973 to 1983) simulated was 8.7%.

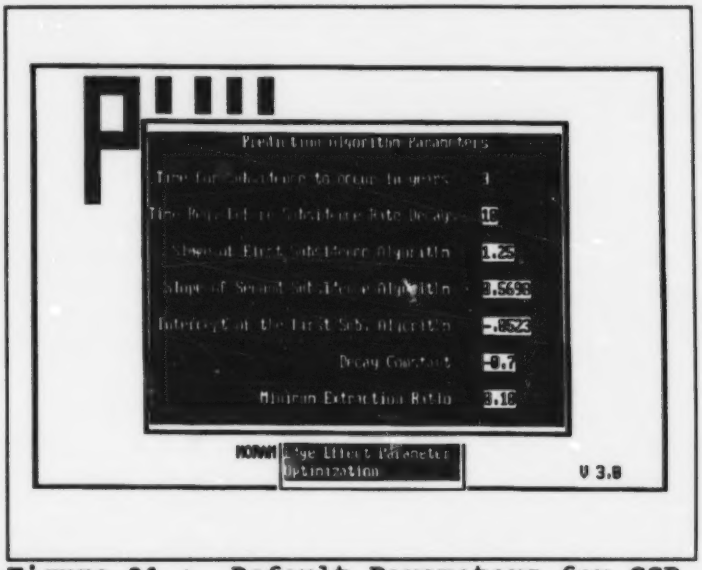
Prediction Algorithm Parameters
Time for Subsidence to Occur in Years 4
Time Period to Subsidence Rate Decay 10
Slope of First Subsidence Algorithm 1.25
Slope of Second Subsidence Algorithm 0.5693
Intercept of the First Sub. Algorithm -.0824
Decay Constant -0.7
Minimum Extraction Ratio 0.10
NORMAL
Edge Effect Parameter Optimization
V 3.8

Figure 31 : Default Parameters for CCP

As seen for the 10th year in Figure 34, Stations 4 and 5 are somewhat over-predicted. This could have been corrected by increasing the zone of influence of the edge effect associated with the end of Block II along with the decay constant. However, since a correction to the field data of approximately 0.4 ft. had been actually applied at CCP, this deviation was ignored.

The parameters associated with the fit shown in Figure 34 are indicated in Figure 32.

6.2 IMCC

A line of 12 points was selected to calibrate the site-specific parameters to IMCC. These points are located over a mining block found in the southwest corner of the K2 mine using the default parameter values indicated in Figure 31, an RMS error of 9% was found for predicted versus measured subsidence for the period spanning 1978 to 1985. A plot of the results for three of the years is

found in Figure 35 at the top.

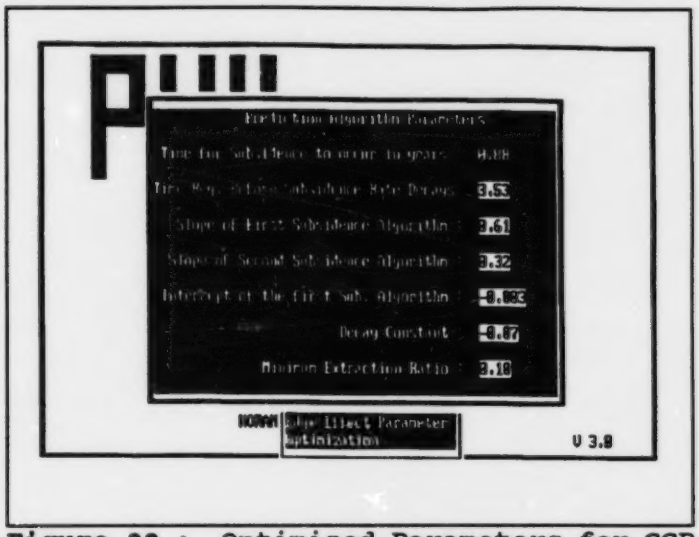

Figure 32 : Optimized Parameters for CCP

As indicated in the figure, even though a low RMS error was found, the algorithm was generally under-predicted and had difficulty in matching the subsidence associated with Station 16. Employing the optimizing routine gave better results than the default parameters, but nonetheless, Station 6 could not be adequately matched as seen in the middle of the figure. The error associated with this run was approximately 5.8%.

A second optimizing run was performed with the field data for Station 6 corrected to fall between the measured data for Stations 5 and 7. The results are found at the bottom of Figure 35. The adjusted subsidence parameters are given in Figure 33. The RMS error associated with this run is 4.7%.

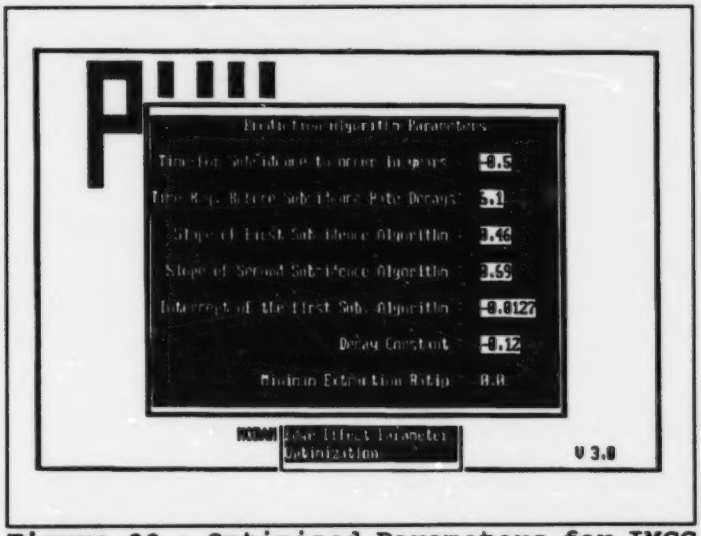

Figure 33 : Optimized Parameters for IMCC

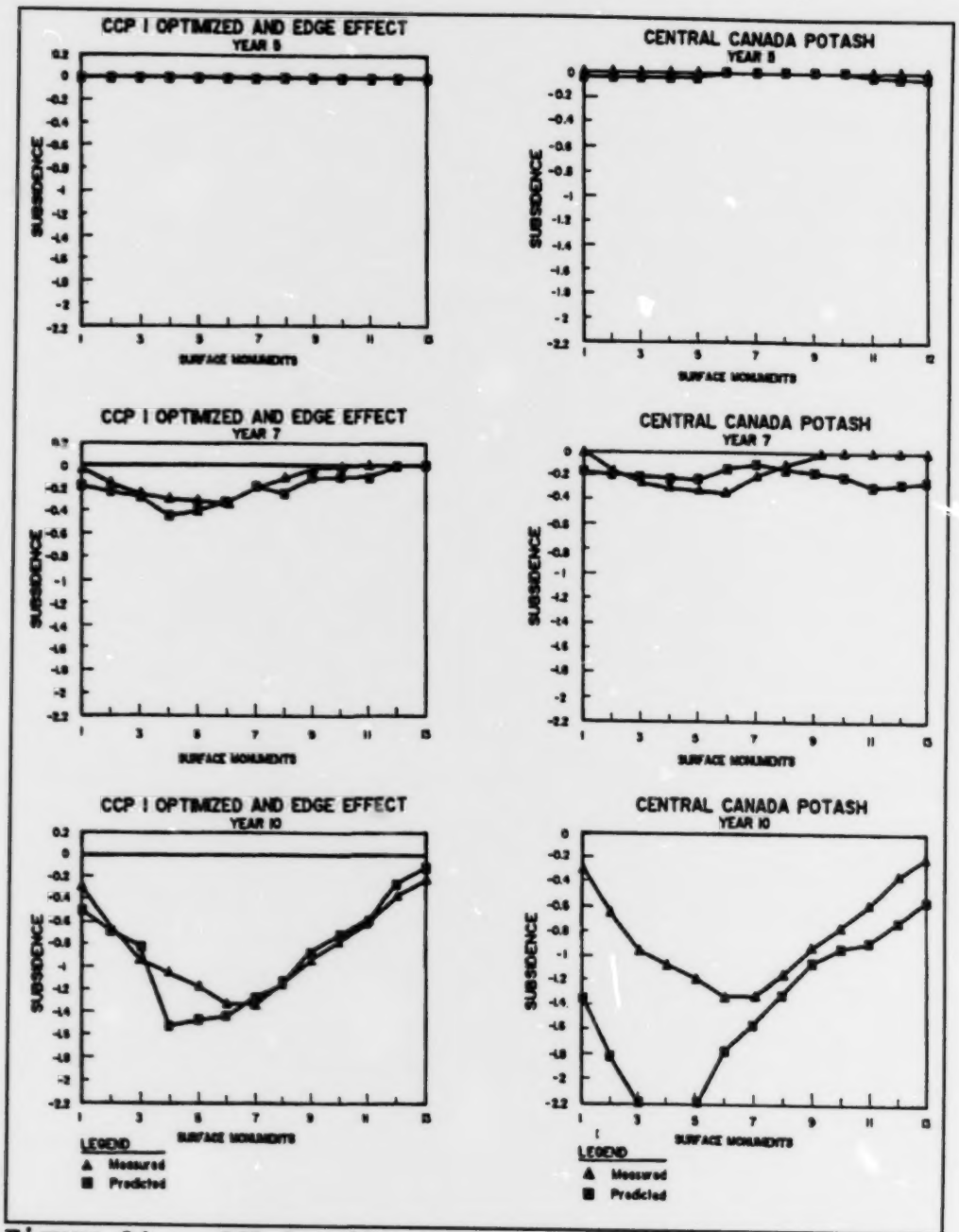

Figure 34 : CCP Results for Subsidence Prediction

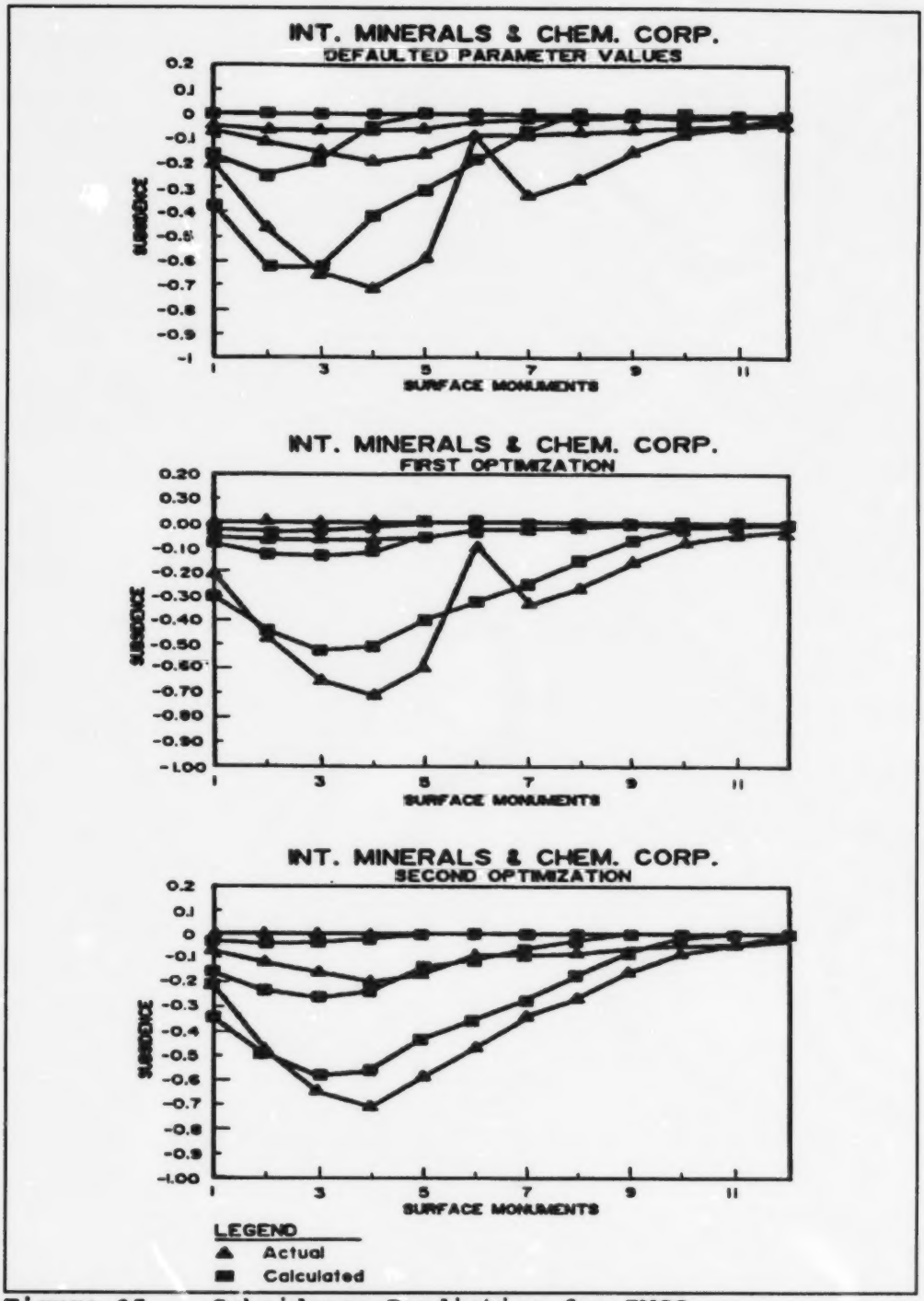

Figure 35 : Subsidence Prediction for IMCC (Years 1,3, & 7)

7. CONCLUSIONS AND RECOMMENDATIONS

1) The PHIL package is a state of the art software package which is user-friendly and interactive using powerful graphic libraries.

2) Calibration of the model to CCP and IMCC field measurements showed good agreement, 8.7% and 4.7% error respectively.

3) The modified zone area method for subsidence prediction used in PHIL properly models subsidence over the Saskatchewan Potash horizon. It is assumed that the potash zone must be near horizontal.

4) The optimizing routine included in the package allows for good calibration of the model to specific sites.

5) It is recommended that further work be performed:

   a) to include more of the prediction parameters used in the prediction algorithm for optimization.

   b) the edge effect routine be modified to handle pillars that do not run N-S or E-W.

   c) more thorough model verification be performed.

GLOSSARY

Due to the confusion that may be caused between computer modelling and mining terms the following index attempts to clarify some of the confusing terminology used in the report.

Borehole :	Is synonymous with drillhole. A borehole is a hole that was used to delimit the actual mineralization zone. Since the model requires a certain number of boreholes to be defined, the user may have to manually interpolate data from the existing drillholes in order to create enough data for the model.
Cell :	Represents one subdivision within a mining grid. It is the cells that are individually dated to determine the extraction within a mining grid.
Mining Grid :	Represents an area of the potash zone, that is user defined, and that is logically grouped within the model. The size and location of the mining grid is defined by selecting an origin, an azimuth and distances along two perpendicular lines. Once the area is defined, a user defined grid is superimposed on the area to create the mining grid. Each smaller area within the grid is called a cell.
Mining Height :	This is the height of potash that is mined from the potash horizon. It does not represent the actual thickness of the horizon.
Surface Benchmark:	Represents the physical or logical surface point that is used for the monitoring and prediction of subsidence. Physically it is the actual surface survey point that is used for subsidence monitoring. Logically it is a point on surface for which the model will predict the amount of subsidence that will occur in the future. The model does not require that the logical surface benchmark correspond to the physical surface benchmark.
Washouts:	This is a geological anomaly.
Zone of Influence:	This should not be confused with the potash zone, it represents the area of ground on surface that is affected by the removal of one cell underground.

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